Simulation the operation of a combined-cycle gas turbine unit with an after burning device in a waste-heat recovery boiler

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Abstract: One of the directions in the development of energy is the study and implementation of combined cycle plants. It is possible to solve a wide range of design and operation problems using mathematical models. A steam-gas power unit based on a GE 6FA gas-turbine unit was studied in this work. In this case, we considered a modernized thermal circuit with an afterburner. In this paper, we consider the method of parametric identification of a mathematical model of a gas turbine in a steady state. The steady-state is taken equal to 80 MW. The difficulty of creating mathematical models of combined-cycle power units is the organization of the computational process. Schematically, the structure of a mathematical model can be represented as a hierarchical set of software modules. The upper-level modules, based on the input data, organize a computational process that includes the organization of calls in the required sequence to the lower level modules in order to form a system of equations that determine the conditions for the combined operation of a combined cycle gas turbine unit. Dependences of changes in the main energy characteristics of a combined cycle plant are shown. Studies have shown the feasibility of using afterburning devices in the cycle of a combined cycle plant.

1. Introduction
At present, the main direction in the modernization of energy capacities is the application of gas turbine technologies. It is most optimal to use gas turbines as part of a combined cycle power unit (CCPU). One of the most effective schemes is a monoblock scheme. It consists of one gas turbine, one steam turbine and a waste-heat recovery boiler. At the same time, gas turbines can have different rated power. Steam turbines are most effective with the supply of high-pressure steam to the head of the turbine and the intermediate supply of low-pressure steam to the turbine flow path. The most common scheme of a waste heat boiler is horizontal design with a vertical design of pipes of heating surfaces. [1-4]

2. Materials and methods
The article describes an example of CCPU-115 consisting of a PG6111FA type gas-turbine unit (GTU) from “GE Energy” (the main characteristics of the gas turbine installation are presented in Table 1) with a rated power of 80 MW, a stationary Kt-46-8.8 cogeneration steam turbine (Table 3) with adjustable heating steam extraction, an Ed-160/14-9.0/0.7-552/210 type waste-heat recovery boiler (WHRB (Table 2)) and necessary accessories to them. [5]
The recovery boiler is designed to generate superheated high and low-pressure steam through the economic and efficient use of heat contained in the combustion products of a gas turbine. The recovery boiler is part of a combined cycle power unit. The scheme of a combined cycle plant with an afterburner is shown in Figure 1. There are various options for placing the afterburner. The most effective installation scheme is in front of the first heating surface of the recovery boiler.

### Table 1. Technical characteristics of a GTU (PG6111FA)

| No. | Characteristic                                          | Meas. unit | Value   |
|-----|--------------------------------------------------------|------------|---------|
| 1   | Power at the generator terminals                       | kW         | 80000   |
| 2   | Atmospheric pressure                                   | kgf/cm²    | 1.013   |
| 3   | Compressor inlet temperature                           | °C         | 15      |
| 4   | Relative humidity at the compressor inlet              | %          | 60      |
| 5   | The pressure of the fuel before the gas module         | kgf/cm²    | 25.9 – 30.8 |
| 6   | The number of stages in the compressor                 | pcs        | 18      |
| 7   | The number of steps in the turbine                     | pcs        | 3       |
| 8   | Air flow                                               | m³/s       | 166     |
| 9   | Compression ratio                                      |            | 15.8    |
| 10  | Air temperature after the compressor                   | °C         | 385     |
| 11  | Flue gas temperature                                   | °C         | 603     |
| 12  | The temperature of the gases after the combustion chamber | °C     | 1325    |

### Table 2. Technical characteristics of a WHRB Ed-160/14-9.0/0.7-552/210

| No. | Characteristic                                          | Meas. unit | Value |
|-----|--------------------------------------------------------|------------|-------|
| 1   | Steam production of high pressure circuit              | t/h        | 160   |
| 2   | Steam production of low pressure circuit               | t/h        | 14    |
| 3   | High pressure steam pressure (abs.)                    | MPa        | 9.0   |
| 4   | Low pressure steam pressure (abs.)                     | MPa        | 0.7   |
| 5   | High pressure steam temperature                        | °C         | 552   |
| 6   | Low pressure steam temperature                         | °C         | 210   |
**Table 3.** Technical characteristics of a steam turbine Kt-46-8.8

| No. | Characteristic                              | Meas. unit | Value                  |
|-----|--------------------------------------------|------------|------------------------|
|     |                                            |            | H-mode | C-mode |
|     |                                            |            |         |        |
| 1   | Power                                      | MW         | 33    | 46     |
| 2   | Parameters of steam HP:                    |            |        |        |
|     | pressure                                   | MPa (kgf/cm²) | 8.8 (90) |        |
|     | temperature                                | °C         | 550   |        |
|     | flow rate                                  | t/h        | 165   | 158.6  |
| 3   | Parameters of steam LP:                    |            |        |        |
|     | pressure                                   | MPa (kgf/cm²) | 0.71 (7.2) |        |
|     | temperature                                | °C         | 208.2 |        |
|     | flow rate                                  | t/h        | 15.6  | 13.1   |
| 4   | Heating thermal load                       | GJ/h (Gcal/h) | 228 (54.5) | - |
| 5   | Pressure in the heating system:            |            |        |        |
|     | nominal                                    | MPa (kgf/cm²) | 0.088(0.9) | - |
|     | range                                      |            | 0.049-0.245 (0.5-2.5) | |
| 6   | Cooling water passing through the condenser (max) | t/h | 8000 | |

**Figure 1.** The scheme of a combined-cycle plant with an afterburning device 1 — a gas turbine generator; 2 — a multistage compressor; 3 — a combustion chamber; 4 — a gas turbine; 5 — a waste-heat recovery boiler; 6 — an afterburning device; 7 — a chimney; 8 — a steam turbine; 9 — a steam turbine power generator.
The waste-heat recovery boiler must meet an important parameter: the ability to work on the sliding parameters for the production of high and low-pressure steam determined by the flow rate and temperature of the gases coming from the gas turbine. The operating range of the gas turbine loads is 25-100%. The afterburning device can be included in the operation at 100% load of the gas turbine, so at lower load damage to the heating surfaces of the boiler may occur. [6-8]

For research, a mathematical model of a combined cycle gas turbine unit is created. The model was created in the software complex AS GRET [9] (Fig. 2).

![Diagram](image)

**Figure 2.** Mathematical model of a CCGT cycle with an afterburning device

GTU – a gas turbine unit; WHRB – a waste-heat recovery boiler; CH – a chimney.

The afterburner system includes elements of a burner device, a valve block module in front of the burner device and an air supply system for needs. The valve block module in front of the burner is designed to control the required gas flow in the gas pipeline. An air supply system is necessary for cooling, purging burners and flame detectors.

Because this gas turbine operates as part of a CCGT power unit, it is necessary to maintain constant power and temperature at the outlet of the gas turbine unit at the baseload. [10-15]. The values of the main parameters of gas turbines when working on standard fuel are the following:

1. The temperature at the engine inlet is 288.15 K (15 °C);
2. The pressure at the engine inlet is 0.1013 MPa;
3. The total inlet airflow rate of 210 kg/s;
4. Power 80000 kW;
5. The temperature of the gases at the outlet is 874 K.

When simulating the operation of a gas turbine, there was a problem of setting engine parameters since several parameters must be set in a zero approximation. However, the exact value can be determined after the calculation is completed. Nevertheless, setting these parameters in the zeroth approximation leads to various kinds of mismatches (residuals) at the end of the calculation according to the model. So, for example, in the calculation the value of the total airflow rate \( G_a \), and the engine speed \( n_1 \) are not known in advance and, consequently, the value of the pressure increase in the compressor, and the required fuel gas flow rate in the combustion chamber are unknown. It is necessary to set the values of these or other parameters in a zeroth approximation using, which can be determined in order for the calculation algorithm formally work. After performing the calculation with these approximate values of the parameters discrepancies, characterized by the lack of power balance on the motor shafts, the balance of gas flow through the characteristic sections of the flow part arise. Other discrepancies are also possible.
The problem arises from eliminating the residuals, i.e. turning them to “zero” by clarifying the values of the parameters specified in the zeroth approximation. Three different methods for solving this problem are known:

1. The method of loopbacks;
2. The method of systems of equations;
3. The method of systems of residuals.

In this study, the method of residual systems is used. It consists in the fact that unknown parameter values are set in the zeroth approximation; the values of all residuals are calculated and stored. Figure 3 shows the residual system that was used for modelling processes in a gas turbine.

![Residual system](image)

**Figure 3.** The residual system that was used for modelling the processes in this study

### 3. Results and Discussion

The oxygen content in the exhaust gases of the gas turbine is 11.5% at a temperature of 15 °C, which is sufficient to organize additional combustion of fuel in the afterburner.

This study examined two modes of operation of a combined cycle gas turbine unit:

1. Operation at rated load of a gas turbine;
2. Operation at the rated load of the gas turbine and operation of the afterburning device of the recovery boiler.

Figure 4 shows a graph of the power changes of a steam turbine and the entire combined cycle gas unit when using an afterburning device in a waste-heat recovery boiler.
Figure 4. Dependence of the power of a steam turbine, gas turbine unit and combined cycle plant on the ambient temperature (with afterburning in a waste heat boiler)

Figure 3 shows a graph of the power of gas, steam turbines and the entire unit in total without afterburning in a waste heat boiler and with afterburning against the ambient temperature. The parameters of afterburning (in particular fuel consumption) are regulated depending on the parameters of the gas turbine and are aimed at maintaining the nominal parameters at the entrance to the head of the steam turbine and thus increasing the power of the steam turbine to a maximum of 46 MW.

With a decrease in the power of the gas turbine due to high ambient temperature, the temperature of the exhaust gases decreases, which affects the amount of steam produced by the recovery boiler, which, in turn, reduces the power of the steam turbine (lower mass flow rate of the steam gives less power with constant heat transfer). [16-21]

It was reaching a 100% load by the gas turbine and ensuring the electric capacity of the CCGT unit the afterburner is turned on switching on the afterburning device allows increasing the steam output of the recovery boiler. An increase in the efficiency of the recovery boiler is equivalent to an increase in the capacity of a steam turbine by 13 MW.

4. Conclusion studies
In this work, we studied the feasibility of using afterburning devices in the cycle of a combined-cycle plant and the operation of the power unit at various temperatures. However, since the design capacity decreases at an ambient temperature above +15 °C, this temperature range (15-35 °C) is highlighted on the graphs.

The study has found that:
1. The use of the afterburning device in the CCGT cycle allows increasing the efficiency and power of the steam turbine;
2. When the afterburning device is turned on, the CCGT power increases by 13 MW (this is achieved by increasing the power of the steam turbine);
3. Using this method allows one increasing the power of the combined cycle plant in the event of a decrease in the power of the gas turbine (for example, with increasing ambient temperature).
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