The first operation results of the gas turbine unit M701F4 as a part of CCP-410 of the Krasnodar TPP after major overhaul

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Abstract. The article contains the reconstruction results of the M701F4 gas turbine unit of the Krasnodar TPP, where it has been in operation since 2011. In May 2019, it was overhauled with the replacement of the gas turbine working blades. In the first two rows, the blades of a new design were used. This allowed reducing the air flow for cooling and forcing the combustion chamber. For research we obtained archival indicators of a standard automation system. They were selected for the periods of operation, which lasted from June 2018 until the moment of major repairs (May 2019) and from June 2019 to January 2020. Data processing was carried out in accordance with State Standard R 55798-2013 (ISO 2314: 2009). The study showed that the reconstruction led to an increase in maximum capacity in the entire range of outdoor temperatures. Under normal conditions and standard air temperature at the compressor inlet equal to +15 ºC, there is an increase by 14.4 MW or by 4.6%. The temperature of the combustion products also increased, the increase was about 15 ºC in the range of outdoor temperatures from +5.6 to +20.0 ºC. The change in the consumption of combustion products is insignificant. We also estimated an increase in the efficiency of electricity generation. It is at the level of 0.5%.

1. Introduction
In recent decades world energy development is inextricably linked with the improvement of the exhaust-fired-boiler cycle. On the basis of this technology, the efficiency of electricity generation at the level of 60% has already been achieved. Simens has developed a new generation of gas turbine units: SGT5-8000HL, SGT5-9000HL and SGT6-9000HL. They have declared the prospect of creating a CCP based on them with an electric efficiency of 65% [1, 2]. Despite the active development of renewable energy sources (according to the forecast [3], they will be able to provide 16% of the total energy consumption by 2035), we can surely assume that in the first half of the XXI century the use of a steam-gas cycle will remain a determining innovative direction in the development of the global heat power industry [4].

In 2008, an energy modernization program was launched in Russia on the basis of capacity supply agreements. Its implementation has led to the fact that the share of combined cycle plants in the country due to their active construction reached 15.95% [5]. For a number of objects the results of this program are already being summed up. At the same time, it’s time for the overhaul of gas turbine units as part of the combined cycle power plant. To clarify the economic performance of the program it is necessary to assess the changes in the operational characteristics of gas turbines after overhaul.
2. Research object
One of the participants in the energy modernization program based on power supply agreements is LUKOIL-Kubanenergo LLC. It operates the Krasnodar TPP. In 2011, a combined-cycle plant CCP-410 was installed at this power plant. It is a three-circuit binary combined-cycle plant consisting of a gas turbine unit M701F4 manufactured by Mitsubishi Heavy Industries, Ltd (Japan), of a waste heat boiler EMA-003-KU (Ep-307/353/41.5-12.6/3.1/0.5-565/560/250) manufactured by OJSC EMAlliance and of a steam turbine T-135 / 145-12.4 manufactured by CJSC Ural Turbine Plant.

Let's give a brief description of the M701F4 gas turbine unit. It is a single-shaft single-hull unit with a constant speed, designed for direct drive of a hydrogen-cooled electric generator. The GTU uses a 17-stage axial compressor with rotary inlet guide vanes. The block-ring combustion chamber contains 20 heat pipes located around the axis of the machine. The turbine consists of 4 stages with jet-type blades. The turbine blades are air-cooled and thermally protected. Factory specifications of the M701F4 GTU are given in table 1 [6]. But when adapting the plant to the conditions of the Krasnodar TPP, they were adjusted. Thus, the electric power of the GTU at the generator terminals under standard conditions and running on natural gas was 303.54 MW, and the net efficiency was 38.84%.

Table 1. Characteristics of the M701F4 gas turbine unit according to the manufacturer's information.

| №  | Parameter                               | Value  |
|----|-----------------------------------------|--------|
| 1  | Rated electrical power (MW)             | 324.3  |
| 2  | Efficiency in a simple cycle with ISO parameters (%) | 39.9   |
| 3  | Turbine inlet temperature (K)           | 1720   |
| 4  | Exhaust gas consumption (kg / s)        | 720    |
| 5  | Exhaust gas temperature (ºC)            | 592    |
| 6  | Turbine speed (rpm)                     | 3000   |

![Figure 1. Photos of the first row of gas turbine blades after modernization.](image-url)
In May 2019, the GTU M701F4 was overhauled with the replacement of gas turbine blades. At the same time, in the first two stages, a new design of the blades was applied. This allowed reducing the air consumption for cooling and forcing the combustion chamber. Photos of the first row of blades are shown in figure 1, of the second one – in figure 2.

This reconstruction led to changes in the characteristics of the GTU. By the time our study began, the unit had accumulated enough operating hours to evaluate them.

3. Calculation methodology

We used standard devices to measure equipment operation parameters necessary for determining energy indicators and building energy characteristics. Samples of averaged indicators of the automation system for three-minute intervals were taken for processing. Totally, there were more than 130 thousand measurements. They were selected for periods of operation that lasted from June 2018 to the time of major overhaul (May 2019) and from June 2019 to January 2020. Data processing was performed in accordance with State Standard R 55798-2013 (ISO 2314:2009).

The study included stationary modes, which are considered to be periods of operation with changes in key external conditions and characteristics of GTU in the standard ranges within 1 hour before the start of the mode. Stationary mode includes the next hour, when these indicators must also be maintained in the specified ranges. We received more than 1800 modes before reconstruction and 309 after it. The results of all stationary modes before processing are shown in figure 3. At this stage we can already observe the increase in GTU capacity in the entire range of outdoor temperatures. Then the modes were culled. For example, in October 2018 the pressure sensor readings of combustion products after a gas turbine were incorrect, etc. In addition, the GTU complex air purifier is equipped with a contact type cooler, which makes it difficult to bring the parameters to normal conditions. The air cooler is usually switched on when the outdoor air temperature reaches $+10^\circ$C and is switched off at a relative humidity of more than 80%, regardless of the temperature. At this stage, such regimes have been excluded from consideration. As a result, the number of stationary modes decreased: there

![Figure 2. Photos of the second row of gas turbine blades after modernization](image-url)
were 245 modes before reconstruction and 56 one after reconstruction. The data were obtained in a wide range of outdoor temperatures from -0.9 °C to + 23.7 °C. The barometric pressure was in the range of 100.1-101.8 kPa, and the relative humidity was 35.3-99.9%. In all modes of gas turbine worked on natural gas.

CCP-410 of the Krasnodar TPP is involved in regulating the frequency of the power system. In this regard, a significant part of the day it works at the technical maximum. During night periods, the load is reset to the technical minimum and after a short period of operation in this mode, the load is again raised to the maximum values. Therefore, with such a wide sample of data, it was not possible to obtain a sufficient number of stationary modes for variable loads.

The next necessary step is to obtain normal conditions, which are accepted as:
- relative humidity – 60%;
- barometric pressure – 101.32 kPa;
- lowest calorific value of fuel – 48175 kJ/kg;
- frequency – 50 Hz
- the total pressure loss on the air inlet filter is 405 mm WG;
- power factor – 0.85.

4. Research results
The results of bringing these stationary modes to normal conditions are shown in figure 4. Electrical power at full opening of the input guide device before major repairs varied from 295.5 MW at + 23.7 °C to 340.0 at – 0.9 °C. After reconstruction, its values range from 317.7 MW at + 20.0 °C to 341.4 MW at + 5.6 °C. To compare the operation of the GTU before and after major repairs, the maximum capacity was calculated under normal conditions using the obtained approximation dependencies (table 2). The effect of the reconstruction decreases with a decrease in the ambient
temperature. Judging by the rate of change in capacity growth, in the zone of negative temperatures, it can reach zero. Verification of this hypothesis in the climatic conditions of the Krasnodar TPP is not possible.

Figure 4. Dependence of the maximum GTU capacity, brought to normal conditions, on the outside temperature.

Table 2. Estimation of changes in the maximum GTU capacity under normal conditions due to reconstruction.

| Parameter                                      | Outdoor temperature (°C) |
|-----------------------------------------------|--------------------------|
|                                               | +5   | +10  | +15  | +20  |
| Maximum electric capacity before reconstruction (MW) | 330.1 | 320.5 | 311.0 | 301.5 |
| Maximum electric capacity after reconstruction (MW)  | 341.6 | 333.5 | 325.3 | 317.2 |
| Growth (MW)                                   | 11.5 | 13.0  | 14.3  | 15.7  |
| Growth (%)                                    | 3.5  | 4.0   | 4.6   | 5.2   |

Figure 5 shows the impact of blade replacement, air flow changes on gas turbine cooling, and combustion chamber forcing on GTU electrical efficiency.

Previously, we noted that the M701F4 GTU operates as part of a combined-cycle gas plant. Therefore, it is important to evaluate the changes in the temperature of the combustion products (figure 6) and their flow rate (figure 7) that occurred in connection with the reconstruction. The temperature of the combustion products increased over the entire studied range of outdoor temperatures. The increase was by about 15 °C. The change in the consumption of combustion products is insignificant.
Figure 5. The dependence of GTU efficiency from the outside air temperature.

Figure 6. Dependence of the combustion temperature of products on the outdoor temperature.

Figure 7. Dependence of the combustion product flow rate on the outdoor temperature.
A sufficient number of stationary modes before the reconstruction allowed us to build the dependence of the GTU capacity on the outdoor temperature with variable outdoor humidity (figure 8).

Figure 8. Dependences of the maximum capacity of the gas turbine on outdoor temperature with variable air humidity before reconstruction:
1 – dependence at the disconnected cooler air and bringing the relative humidity of outdoor air to 60%, 2 – included cooler, external humidity 75%, 3 – enabled cooler, external humidity 45%, 4 – enabled cooler, the humidity of the outside air of 15%.

According to other parameters (except humidity), the capacity was brought to normal conditions. Here we can see that when the air cooler is operating, the humidity of the atmospheric air has a significant influence on the maximum capacity. For example, at a relative humidity of 45% and a temperature of 25.5 °C, the maximum capacity takes the value 305.0 MW, but if the air humidity to the cooler is 15% at the same temperature, the capacity will be 309.8 MW. This effect is caused by the fact that the lower the initial humidity of the air, the more water vapor can be perceived into the cooler and the lower the air temperature will fall after it.

Conclusion
In this study, we evaluated the application of the new design of blades with a change in air consumption for their cooling and forcing the combustion chamber of the M701F4 gas turbine unit. The reconstruction resulted in an increase in maximum capacity over the entire outdoor temperature range. Under normal conditions and standard air temperature at the compressor inlet of + 15 °C, we observed an increase of 14.4 MW or 4.6%. The temperature of combustion products also increased, with an increase of about 15 °C in the outdoor temperature range from + 5.6 to + 20.0 °C. The change in the consumption of combustion products is insignificant. This should have led to an increase in the capacity of the heat recovery boiler and steam turbine CCP-410. Their exact definition is a prospective study. We estimated the efficiency increase for electricity generation. It is at the level of 0.5%. We
established the inverse relationship between the maximum load and the humidity of the outdoor air during operation of the contact air cooler.

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