Improving the efficiency of combined-cycle plant by cooling incoming air using absorption refrigerating machine

D I Mendeleev, G E Maryin and A R Akhmetshin*

Kazan State Power Engineering University, 420034, Russian Federation, Kazan, Krasnoselskaya Str., 51

* E-mail: ahmetshin.ar@mail.ru

Abstract. The purpose of the paper is to study and analyze the possibility of increasing the power of combined cycle gas turbine (CCGT) unit during the period of positive ambient temperatures. The other aim is to study usage of an absorption refrigerating machine in a CCGT cycle to increase its energy efficiency. The third aim is to analyze the operation of 110 MW combined-cycle power unit at various ambient temperatures, and to obtain alterations in the main CCGT characteristics when the ambient temperature changes. Calculations of the thermal scheme of a gas turbine were carried out using mathematical modeling, the steam turbine was calculated basing on the guidelines. The possibility of increasing the capacity of a CCP-110 MW was studied and analyzed. The conducted studies allowed us to conclude that the use of absorption refrigerating machine in the cycle of a combined-cycle plant can improve the efficiency of the unit, increase profits from power generation, and reduce penalties for non-compliance with the load schedule.

1. Introduction

The problem of moral and physical aging of the power equipment park is very relevant now. Reconstruction and commissioning of new equipment of thermal power plants should be carried out using new technological solutions and new technologies. The energy strategy of the energy sector up to the year 2030 includes commissioning of new natural gas power units of combined-cycle gas turbine plants (CCGTP) with capacities of 100, 200 and 450 MW [1].

Currently, all power units of CCGTP operate at the wholesale electricity and capacity market, where it is necessary to carry out the planned dispatch schedule set by the system operator. In case of deviation from the specified load by an amount exceeding 2% of the declared maximum on-power, but not less than by 1 MW at the end of an hour, for more than 4 consecutive hours, and when this deviation is not related to the disconnection of the generating equipment, the corresponding decrease in maximum power are recorded for all hours [2,3].

The purpose of the paper is to study and analyze the possibility of increasing the power of combined cycle gas turbine unit during the period of positive ambient temperatures. The other aim is to study usage of an absorption refrigerating machine in a CCGT cycle to increase its energy efficiency.

2. Materials and methods

The article describes an example of CCGTP-220, consisting of two 110 MW units, each of which consists of a gas-turbine unit (GTU) of PG6111FA type (from “GE Energy”) with a rated power of 77 MW, a stationary cogeneration steam turbine KT-33/36-7.5/0.12 with adjustable heating steam...
extraction, a waste-heat recovery boiler (WHRB) of E-114/16-8.1/0.7-535/218-3.8vv type, and necessary accessories to them.

The instantaneous power schedule is set by the production and technical department (PTD) and a deviation of 2% or 3 MW is allowed, but the PDT sees only the final power on the charts. The operating personnel, depending on the actual equipment condition and various circumstances, determines the work process that keeps the schedule and equipment is in the best possible operating mode [4]. An example of the unfulfilled schedule of instantaneous power block is presented in Figure 1.

![Figure 1. Unfulfilled instant capacity chart.](image)

Figure 1 shows the deviation between the planned and actual schedule of electrical load in the summer period. The main problem of deviation from the planned electrical load schedule is to reduce the power generated by the gas turbine due to the increase in the work of air compressing into the compressor.

The costs for air compressing into a compressor caused by an increase in outside air temperature consist of useful work of a gas turbine $\text{UGT}$ and of fuel burned in combustion chamber $b_f$, the specific consumption of which increases when the GTU operating mode deviates from the nominal one (Figs. 2,3).

For a combined cycle power plant, the share of output power which is accounted for by the gas turbine is about two-thirds, and the rest is provided by a steam turbine. In most modern CCGTPs, a waste heat recovery boiler and steam turbine are adjusted according to sliding pressure control logic for better thermal efficiency. Following this control logic, the steam turbine inlet valve is fully open in most operating states. Thus, the steam storage in WHRB drum will be insignificant and, therefore, there will be an inherent delay between the increase in fuel supply into the gas-turbine combustion chamber and a noticeable change in the output power of the steam turbine. Consequently, the transient characteristics of modern combined-cycle power plants at frequency drop completely depend on the gas turbine performance. In other words, only two thirds of the aggregate power, which is related to the gas turbine, can be used during transient processes [5-7].

Therefore, it is important to study and analyze the possibilities of increasing the power of combined-cycle gas turbine plant, the operating modes of power unit and alteration of the main indicators of CCGTP operation when the ambient temperature changes.
Figure 2. Hourly power generation by the unit and the total deviation from the task for a certain day (Green - the schedule is fulfilled, yellow - it is fulfilled with minor deviations, red – it was not fulfilled).

![Figure 2](image)

With a decrease in GTU power as a result of decrease of flow, pressure and temperature of high-pressure steam, the power of the steam turbine decreases. (Tables 1,2).

*I* (Ideal conditions and clean filters) $P_{atm} = 105$ kPa = const, humidity$ = const = 30\%$, pressure drop at the compressor inlet $\Delta P_{in} = 160$ mmWC = const, static pressure at the turbine outlet $P_{out} = 270$ mmWC = const.

![Figure 3](image)

Figure 3. Capacity deviation chart for GTU in warm period.
Table 1. Relationship between $N_{GTU}$ and the outdoor air temperature (Ideal conditions).

| $t_a$ | -40 | -30 | -20 | -10 | 0  | 10  | 15  | 20  | 30  | 40  |
|-------|-----|-----|-----|-----|----|-----|-----|-----|-----|-----|
| $N_{GTU}$ | 88.52 | 88.23 | 87.72 | 86.8 | 84.4 | 81.12 | 79.3 | 77.21 | 71.2 | 67.9 |

II (Adjusted for contaminated filters) $P_{atm}=101.4$ kPa=const, humidity=const=30%, pressure drop at the compressor inlet $\Delta P_{in}=100$ mmWC = const, static pressure at the turbine outlet $P_{out}=270$ mmWC=const.

Table 2. Relationship between $N_{GTU}$ and the outdoor air temperature (II)

| $t_a$ | -40 | -30 | -20 | -10 | 0  | 10  | 15  | 20  | 30  | 40  |
|-------|-----|-----|-----|-----|----|-----|-----|-----|-----|-----|
| $N_{GTU}$ | 86.04 | 85.73 | 85.38 | 84.21 | 82.2 | 79.11 | 77.31 | 75.21 | 69.48 | 66.21 |

The problem of increasing the GTU power can be solved by supplying additional working fluid to the flow part of the turbine. In articles [8-9], water injection into a gas turbine compressor is considered, and this injection results in an increase in power. This supply of additional working fluid is caused by a number of problems, such as the possible ingress of water droplets in the flow part of the compressor and modernization of AFCS, steam supply to the flow part of the gas turbine. The steam expansion in a gas turbine occurs up to atmospheric pressure, while in steam turbines the expansion occurs up to a pressure of 0.45-0.3 kPa, which leads to lower injection efficiency.

Cascade air cooling in compressor is one of the most effective ways to increase the power of a gas turbine [10], implementation of this project is very expensive in practice, since besides buying a large amount of auxiliary equipment, it is necessary to upgrade the flow section. One of alternative ways of injecting water or steam into the flow part is injection of carbon dioxide. [11, 12]

The analysis of static characteristics of CCGTP -110 MW allows us to conclude that when the air temperature is above +15 °C, at maximum load of the gas turbine unit a drastic reduction in power unit efficiency is observed.

The change in temperature at the inlet to AFCS (Fig. 4) has the main influence on power produced by the gas turbine unit. The lower is the temperature, the greater load (greater power) the gas turbine can take (deliver). At the same time, at a constant temperature in the combustion chamber, the power of the gas turbine plant increases and efficiency increases. Therefore, the ambient air temperature will also affect the IGV opening angle, gas flow rate, exhaust temperature.

Figure 4. Relationship between GTU power and the temperature at the compressor inlet.

In order to reduce the impact of high temperature of air compressed in the compressor on electricity generation by the combined-cycle gas turbine plant, it was proposed to apply pre-cooling of air before compressor. As a source of cold it is proposed to use absorption refrigerating machine (ARM) [14-18]
The principle of operation of absorption refrigerating machine is based on certain properties of the refrigerant and absorbent, which provide heat removal, cooling and maintaining the required temperature conditions.

At present, the industry widely uses absorption lithium-chromium refrigerating machines with two-stage steam generation of the working substance (ARM) to produce cold in the area of positive temperatures for various technological needs. The effectiveness of ARM depends on parameters of external heat sources, temperature drops in the apparatus, cost of dry machine, amount of lithium bromide in heat exchangers, cost of heating source (steam, hot water, natural gas combustion products) and other factors.

ARM can be connected to the AFCS heat exchanger in parallel with the anti-icing system. In winter, when the external air temperature is 0 °C, the heat exchanger can operate in the air heater mode before the compressor, in the summer period the anti-icing system is turned off, the air cooling system (from ARM) is activated before the compressor. Economic calculations are presented in Table 3.

Table 3. Economic calculation of ARM use in the CCGTP cycle.

| No | Characteristics                                      | Expression for calculation | Meas. unit | Value          |
|----|------------------------------------------------------|----------------------------|------------|----------------|
| 1  | Production of electricity per day at a load of 110 MW | Passport data              | ths. kWh   | 2 640          |
| 2  | Underproduction of e/e due to high outdoor temperature| Analysis of underproduction in April-October of 2016 | ths. kWh | 12 206.86     |
| 3  | Lost profits of the enterprise, associated with a decrease in the volume of generated electricity | \( E_{e/e} = (2410 - 1440) \times 12 206.891 \times 2 \) | ths. rub   | 23 681.3       |
| 4  | The cost of selling electricity \( C_{sell} \)       | Actual data                | rub/ ths. kWh | 2 410          |
| 5  | The cost of generated electricity \( C_{gener} \)     | Actual data                | rub/ ths. kWh | 1 440          |
| 6  | Specific fuel consumption for production of 1 kWh of e/e | Actual data                | grams of fuel/kWh | 252            |
| 7  | Capital costs, rubles                                | \( C_{cap} \)              | rub         | 95 013 693     |
| 8  | Lost profit from the sale of e/e at wholesale market for electricity and power | \( E_{e/e} \)              | rub         | 23 681 369     |
| 9  | Cash losses from penalties for short supply of capacity | \( E_{g,tot} \)           | rub         | 14 703         |
|    | The total savings from usage of two                  |                            |            | 411.79         |
| 10 | ARMs for 2 GTU without operating costs               | \( E_{e/e} + E_{g,tot} + E_{st} \) | rub/year    | 38 445 661     |

3. Conclusions

The use of an absorption refrigerating machine in the cycle of a combined-cycle gas turbine plant does not imply changes in the design of the main equipment (in particular, a gas turbine or compressor), thereby minimizing both costs and time for modernization.

The unit allows the equipment to operate at nominal (basic) parameters, which will result in removal of technical limitations on power and fulfillment of the load schedule, increasing output, profit, and will also reduce or completely eliminate penalties.

Considering the fact that the equipment can be on optimal operating parameters for a longer time, its reliability, economy and safety are increased, and it is also possible to regulate power over wider limits (in the summer period), depending on the specified electrical load schedule.

The total savings from the introduction of two ARMs for 2 GTU installations excluding operating costs will be 38,445,661 rubles.
References

[1] The energy strategy of Russia for the period up to 2030 (approved by the Order of the Government of the Russian Federation No. 1715-p dated November 13, 2009) [Electronic resource]: // Reference Legal System Consultant Plus.

[2] Ivanova P, Grebesh E, Linkevics O 2018 Optimisation of combined cycle gas turbine power plant in intraday market: Riga CHP-2 example Latvian Journal of Physics and Technical Sciences 55(1) 15-21.

[3] Government Decree dated October 24, 2003 N 643 “On the rules of the wholesale electricity market (power) during the transition period” [Electronic resource]: // Reference Legal System Consultant Plus.

[4] Mendeleev D I, Marin G E 2018 Factors affecting the ability to generate flowcharts. Modern technology in the energy sector. All-Russian Specialized Scientific and Practical Conference of Young Specialists. March 29-30 36-40 ISBN 978-5-905858-22-2

[5] Hou G L, Gong L J, Dai X Y, Wang M Y, Huang C Z 2018 A Novel Fuzzy Model Predictive Control of a Gas Turbine in the Combined Cycle Unit // Complexity 18.

[6] Mohamed O, Wang J H, Khalil A, Limhabras M 2016 Predictive control strategy of a gas turbine for improvement of combined cycle power plant dynamic performance and efficiency // Springerplus 5 20.

[7] Saeed Bahrami, Ali Chaffari, Magnus Genrup, Marcus Thern 2015 Performance Comparison between Steam Injected Gas Turbine and Combined Cycle during Frequency Drops Energies 8, 7582-92, ISSN 1996-1073

[8] Berkovich A L, Polishchuk V G, Nazarenko A V 2015 Forcing stationary gas turbines with optimal injection of water into the compressor. St. Petersburg State Polytechnic University Journal of Engineering Science and Technology 2(219) 33-40.

[9] Kudinov A A, Gorlanov S P 2014 Improving the efficiency of the gas turbine installation by injecting water vapor into the combustion chamber of the NK-37 engine Vestnik SGASU Urban planning and architecture 1(14) 103-9.

[10] Shigapov A B, Shigapov A A 2010 Regular exhaust gas heat of GTU in schemes with intermediate air cooling. Proceedings of the higher educational institutions. Energy sector problems 20-28

[11] Maryin G E, Mendeleev D I. 2018 Summing up various substances to improve the energy characteristics of gas turbines. Modern technology in the energy sector. All-Russian Specialized Scientific and Practical Conference of Young Specialists. March 29-30 41-5 ISBN 978-5-905858-22-2

[12] Gonzalez-Diaz A, Alcaraz-Calderon A M, Gonzalez-Diaz M O, Mendez-Aranda A, Lucquiaud M, Gonzalez-Santalo J M 2017 Effect of the ambient conditions on gas turbine combined cycle power plants with post-combustion CO2 capture Energy 134 221-33.

[13] Fong K F 2017 Investigation on year-round dispatch of multiple chillers in trigeneration system for high-rise building application // Proceedings of the 9th International Conference on Applied Energy 142 1502-8.

[14] Yu F W, Chan K T, Yang J, Sit R K Y 2018 Cooling effectiveness of mist precooler for improving energy performance of air-cooled chiller Thermal Science 22(1) 193-204.

[15] Zuniga-Puebla H F, Vallejo-Coral E C, Galaz J R V 2019 Thermodynamic analysis of one and two stages absorption chiller powered by a cogeneration plant Ingenius-Revista De Ciencia Y Tecnología 21 41-52.

[16] Benrajesh P, Rajan A J 2016 Design and analysis of a two-stage adsorption air chiller // 2nd International Conference on Frontiers in Automobile and Mechanical Engineering;

[17] Sathyabamam U et al 2016 IOP Conference Series-Materials Science and Engineering 197

[18] Galimov L V 1997 Absorption chillers and heat pumps. Textbook, Astrakhan: Ed. ASTU 226
[19] Cozzolino R 2018 Thermodynamic Performance Assessment of a Novel Micro-CCHP System Based on a Low Temperature PEMFC Power Unit and a Half-Effect Li/Br Absorption Chiller *Energies* **11**(2) 21.