Improving the maneuverability and thermal efficiency of modern cogeneration systems based on gas turbine power plants

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Abstract. The paper is devoted to the issue of increasing the maneuverability and efficiency of modern cogeneration systems based on gas turbine power plants. Promising solutions for increasing the maneuverability of GTU-CHPP by using heat accumulators and the formation of a preheating circuit of the network water are considered. It is shown that in the non-heating period, it is possible to increase both the thermal efficiency and the generated electric power by installing a heat exchanger in front of the compressor. The calculation results show that this provides an increase of 0.4% in the net electrical efficiency by and an increase 3.3% in the annual electricity generation.

1. Introduction

The long-term centralized development of the electric power industry in Russia the high efficiency of combined production, and climate features (the thermal power consumption is two times higher than the electric power consumption) has led to the wide use of CHPPs and centralized power systems based on them in the country. These centralized power systems meet up to 90% of the urban heat and electricity demands [1, 2, 3].

During the planned economy period, CHPPs were rationally integrated into the unified energy system of the country and exhibited high performance. However, after the transition to a market economy, the position of CHPPs has deteriorated significantly due to the weak adaptability of this type of generation to market conditions. Over the past 20 years, heat supply from CHPPs decreased by a factor of more than 1.5. Despite this negative trend, CHPPs still play a major role in the energy supply to consumers. They account for about 47% of electricity generation by thermal power plants and 37% of heat supply by heat sources [4, 5, 6].

The main advantages of cogeneration of energy products at CHPPs are [6, 7]:

- low specific fuel consumption in the combined generation of electricity and heat,
- the possibility of separating conditionally variable costs (fuel savings due to district heating) between electricity and heat, depending on the situation in the power markets,
- production of electricity close to the place of its consumption,
- increased reliability as a heat source.
At the same time, combined production at CHPPs has a number of disadvantages that do not allow its advantages to be fully realized in market conditions [6, 8]:

- low maneuverability in terms of electrical unloading of generating equipment operating in cogeneration mode due to the need to cover the heat load (impossibility of reducing the supply of electrical energy without simultaneously reducing the supply of heat),
- a small number of hours of operation of the installed capacity in heating mode due to the seasonal nature of the demand for heat power.

The electricity generated by different types of CHPPs in the heating cycle ranges from 25 to 150% of the amount of heat consumption. At the same time, the unit cost of electricity production is approximately the same, regardless of the type of power plant (Table 1). Thus, by changing the composition of power equipment and production technology (heat cycle), it is possible to produce electricity and heat in different ratios with the same efficiency. Since CHPPs are usually built, expanded, and reconstructed over decades (due to a gradual increase in the load and a change in the structure of electricity and heat production), many plants have power units of various types [5, 6, 9, 10].

Table 1. Comparative indicators of specific fuel consumption for various types of TPPs

| Power plant type and operating mode | Products | Fuel utilization factor, % | Specific fuel consumption for electricity production, g / kWh |
|------------------------------------|----------|---------------------------|------------------------------------------------------------|
| STU-CHPP heating mode              | electricity and heat | 82                         | 150                                                        |
| CCGT-CHPP heating mode             | electricity    | 35                         | 351                                                        |
| GTU-CHPP condensing mode           | electricity and heat | 82                         | 150                                                        |
| CPP combined production            | electricity    | 39                         | 315                                                        |
| CCGT plant                         | electricity    | 55                         | 212                                                        |
| GTPP                               | electricity    | 35                         | 340                                                        |

In connection with the development of distributed generation, GTU-CHPPs, which have relatively low capital costs and a high fuel utilization factor, have gained particular importance in ensuring independent power supply of regions [1, 2]. At the same time, the development of independent resource-saving regional power systems based on GTU-CHPPs necessitates an increase in their capacity and efficiency. This requires the development of new highly efficient thermal schemes.

2. Methods

Despite the possibility of significant fuel savings in the joint production of energy products at CHPPs, combined generation is being pushed out of the production structure of territorial power systems. The reason for this is the technological limitations of the production process, such as low maneuverability, a limited share of energy production based on heat consumption during the year, and a decrease in electricity generation during heat extraction.

Uneven consumption of energy products forces power plants to operate with frequent changes in operating modes, which leads to a decrease in the efficiency of the production process and a reduction in the service life and reliability of the main generating equipment. There are several ways to level the load curve of thermal power plants [11, 12]:

- use of multi-part tariffs to stimulate steady consumption of energy products by consumers;
- peak-load operation of part of the thermal power plant equipment;
- energy storage at thermal power plants and the use of additional heating circuits to heat the network water.

The use of energy storage systems is the most promising production and technological solution for leveling the load schedule and increasing the maneuverable characteristics of CHPPs. Increased
maneuverability is achieved by increasing the ability of a power system to quickly respond to a change in its power, characterized by the adjustable range of operation and the rate of change of load.

Whereas the use of energy storage systems is limited by their low capacity and high cost, the use of heat accumulators is much more technological and economically feasible [13, 14]:

- significant expansion of the power regulation range (20–25% for electricity supply and 40-50% for heat supply),
- high rate of capacity changes due to short-term and fairly simple operations (start-stop of pumps, opening-closing of valves),
- relatively low capital costs for additional capacity.

The most practical solution is to use hot water storage tanks as heat accumulators in the heat supply scheme from CHPPs. At the same time, to ensure operability, it is necessary to have two accumulator tanks for separate storage of hot and cold water. During peak electrical loads, excess heating water is discharged from the cold water storage tank. Having passed through the network heaters, the excess part of the already heated network water is directed to a hot water accumulator. Increasing the heat load leads to the generation of additional electricity based on heat consumption. During the hours when the electrical load is disconnected, water from the hot heating water accumulator is supplied to the input to the network heater. The heat load of the turbine unit is reduced, and its electrical power is proportionally reduced.

It is also possible to increase the generation of electricity based on heat consumption by including a preheating circuit of network water in the thermal scheme of a power plant (Figure 1). This solution is most effective for GTU CHPPs [15, 16, 17].

Air is pumped in by a compressor, compressed to a higher pressure, and sent to the combustion chamber. Fuel (natural gas) is also fed into the combustion chamber, where it burns, providing a constant supply of heat. The compressed air mixes with the combustion products to form a high-temperature gas that enters the gas turbine, where it expands to atmospheric pressure and does useful work by generating electricity. After the turbine, the exhaust gases are utilized in a gas-water heat exchanger, where they are used to heat water in the heating system and, accordingly, to supply heat to consumers.

![Figure 1. Diagram of a GTU-CHPP with a preheating circuit for network water](image)

The gas-water heat exchanger consists of two heating surfaces. The first heating surface along the gas path serves to transfer heat to the coolant circulating in a closed preheating circuit of return network water. For this, a water-to-water heat exchanger is used. The heated network water is directed to the second heating surface of the gas-water heat exchanger, where it is further heated to the required temperature according to the temperature schedule of the heating network and is supplied to the consumer.

3. Results and discussion

Figures 2 and 3 show the results of performance analysis showing the advantages of using a preheating circuit for network water in a GTU-CHPP.
Comparison of the energy efficiency of thermal schemes of GTU-CHPP is made on the basis of the condition of covering a given heat load schedule for climatic conditions typical for the Moscow region. The ratio of the heat load in the non-heating season to the maximum heat load is assumed to be 1:5. The main characteristics of thermal schemes are shown in Table 2.

Table 2. Main characteristics of thermal schemes of GTU-CHPP

| Specifications                                                      | Standard scheme          | Scheme with preheating circuit |
|---------------------------------------------------------------------|--------------------------|--------------------------------|
| Number of power units, pcs                                         | 3                        |                                |
| Gas turbine model                                                  | Siemens SGT-400          |                                |
| Net electric power of CHPP in design mode, MW                       | 41.2                     |                                |
| Heat output of the CHPP in design mode, MW                         | 83.4                     |                                |
| Design point of calculation of a gas-water heat exchanger, °C       | -2.2                     |                                |
| Design point of calculation of the second in the course of gases heating surface of the gas-water heat exchanger, °C | -                         | 2                              |
| Peak source of heat                                                | Peak hot water boilers   |                                |
| Heat supply control method                                         | Uniform unloading of gas turbines and shutdown of the number of operating power units |

The advantage of using a preheating circuit for network water in a GTU-CHPP is an increase in the electrical power generation based on heat consumption, primarily in summer, when the demand for heat is quite low. A disadvantage is an increase in electricity consumption for own needs due to the need to
ensure the operation of the circulating pump in the closed circuit of preliminary heating of network water. The thermal efficiency of a GTU-CHPP can be increased using the following thermal diagram presented in Figure 4.

![Figure 4. Schematic diagram of a highly efficient GTU-CHPP](image)

Atmospheric air passes through an air cleaning device (1), and enters compressor (3), where it is compressed and directed to the inlet of combustion chamber (4). After the combustion of the hot mixture and the generation of useful work in gas turbine (5), hot gaseous combustion products are directed to the inlet of the hot coolant circuit of the gas-water heat exchanger (7), where they heat the heating water entering the cold circuit of the heat exchanger after the hot coolant circuit of the evaporative heat exchanger (10). At the outlet of the hot coolant circuit of the gas-water heat exchanger (7), gaseous products are discharged into the atmosphere in the form of flue gases. Network water from the outlet of the coolant circuit of the gas-water heat exchanger (7) is directed to the consumer. Electric generator (6) is used to generate a payload and electricity to power a compressor (3). Calculations for the proposed thermal scheme show that heating of atmospheric air from -20 °C to 10 °C in the heat exchanger during the heating period allows increasing the net electrical efficiency by 7.5% compared to the standard CHPP scheme by reducing the cost of electricity for heating air in the electrical heat exchanger (2). In turn, cooling of atmospheric air in the non-heating period from 20 °C to 10 °C in the heat exchanger (7) in the non-heating period allows increasing the net electrical efficiency by 0.4% due to an increase in air consumption at the compressor inlet (3) and due to a decrease in the specific power of the compressor. This provides a 3.3% increase in annual electricity generation and a 5.8% increase in annual heat supply.

**Conclusions**

Currently, the construction of efficient cogeneration systems is the most important condition for solving the problems of energy and resource conservation outlined in the Energy Strategy of Russia for the period up to 2035. The cogeneration system involves the implementation of joint heat and power generation at CHPPs using steam turbine and gas turbine equipment. In connection with the development of distributed generation, GTU-CHPPs, which are distinguished by relatively low capital costs with a high fuel utilization factor, have gained particular importance in ensuring the independence of power supply to the regions.

Despite the above advantages, the development of independent resource-saving regional power systems based on GTU-CHPP requires an increase in their capacity, maneuverability, and efficiency. This necessitates the development of new highly efficient thermal schemes.

The most effective solution for increasing electricity generation in combined production for GTU-CHPPs is to use a preheating circuit for network water in the thermal scheme of the power plants. At the same time, this leads to an increase in electricity consumption for own needs.

It is possible to increase the thermal efficiency simultaneously with the supplied electric power by installing a heat exchanger in front of the compressor in the non-heating period. Calculation results show that a 0.4% increase in the net electrical efficiency is due to an increase in air consumption at the compressor inlet and a decrease in the specific power of the compressor. This provides a 3.3% increase in annual electricity generation by and a 5.8% increase in annual heat supply.
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