Combined-cycle gas turbine plant based on steam-turbine unit and a parallel superimposed gas-turbine plant with waste heat recovery boiler

V Fomin and A Kalyutik

Peter The Great Saint-Petersburg Polytechnic University, Saint-Petersburg, 195251, Russia

* E-mail: kalyutik@yandex.ru

Abstract. We present a schematic diagram and the results of calculations of operating modes of the combined-cycle gas turbine plant (CCGTP) with a parallel superimposed gas-turbine plant (GTP). It is shown that at part-load operation in order to increase the efficiency of the unit, it is advisable to alter the steam turbine power while remaining the gas turbine power constant.

1. Introduction

Combined-cycle gas turbine plants in the form of various schemes of superimposed units and extensions to the existing equipment can be applied for modernization and reconstruction of morally and physically obsolete power units K-200-12,7 and K-300-23,5, which were commissioned in the middle of the 1970s [1-6].

The volume of the upcoming renovation (reconstruction) is quite significant, the total number of units with a capacity of 150-300 MW is 120, and their installed capacity is 22.76 mln. kW [7-9]. The geography of their location covered the entire European part of Russia [10]. Power units with a capacity of 300 MW were commissioned at the following power plants: Konakovskaya (8 pcs.), Novocherkasskaya (8 pcs.), Troitskaya (4 pcs.), Sredneuralskaya (3 pcs.), Kostromskaya (4 pcs.), Kashirskaya (3 pcs.), Kirishskaya (3 pcs.) [11-13]. Thus, the volume of installed capacity of K-300 power units to be reconstructed due to their physical deterioration is currently about 5 million kW. One of the possible ways to reconstruct the outdated units of 300 MW capacities is to upgrade them according to schemes with various steam-gas superimposed units and extensions.

2. Materials and methods

Steam-gas superimposed units operating in parallel with the main steam-turbine unit have different thermal circuits [14]: with steam supply from a waste heat recovery boiler (WHRB) to the hot steam intermediate-heating line, or to the steam extraction line to the heater of steam turbine regeneration system, or to the steam line of "hot" steam from the main boiler. In the latter scheme, WHRB generates steam of high parameters, therefore, the heat supply to WHRB is the largest comparing to other schemes. And this determines a higher efficiency of CCGTP, in comparison with other schemes using extensions.
The steam and gas power unit under consideration consists of a steam turbine unit with steam boiler and steam turbine, added by a gas turbine unit with waste heat recovery boiler (WHRB) in a parallel circuit. The principal thermal scheme of this superimposed unit is shown in Figure 1.

Figure 1. Principal scheme of a combined steam-gas plant.

Addition of gas turbines (GT) with WHRB to steam-turbine units using the parallel scheme allows obtaining rapid capacity expansion based on the reconstruction of steam turbine units that have exhausted their resources with minimal capital expenditures. The increase in electrical power and efficiency of the unit is associated with obtaining additional power, which includes GTP power and the increase in STP power due to generation of additional steam in WHRB and partial replacement of steam extraction for WHRB heat recovery, as well as an increase of feed water heating temperature before the boiler.

In the scheme, it is advisable to use a horizontal, straight-through WHRB, which contains three heating sections: a gas condensate heater (GCH), a high pressure economizer (HPEc), and sections of high pressure steam generation and superheating, i.e. generator-steam heater (GSH). The WHRB thermal circuit also contains control valves (CV) with the following control parameters:

- CV1 is for air temperature after the air-cooler GTE-60;
- CV2 is for condensate temperature before WHRB;
- CV3 is for temperature of heating water after the water heater of fuel (WPT);
- CV4 is for steam temperature after WHRB;
- FCV (Feed Control Valve) is for WHRB exhaust gas temperature.

Schemes of turbines K-300-23,5 and K-200-12,7 can be adopted as variants of STP thermal scheme.
Condensate to GCH is supplied from the main condensate line at the back of LPH1, bypassing LPH2, LPH3 and LPH4, and changing the flow rate by means of feed control valve (FCV). From GCH, condensate enters the air cooler (AC), if it is present in the GTP circuit, then to the deaerator. The required condensate temperature before the GCH is provided either by recirculating the hot condensate or by changing the condensate flow rate supplied from the LPH2 condensate collector to the mixer (MX) using the CV2.

When GTP is running, from the deaerator (D) water is fed to HPEc and to a water heater of fuel (WHF). Heating water for WHF is supplied either from a booster pump or from an intermediate stage of a feed pump (FP).

Water from HPEc flows partly into the HPH line, partly into the WHRB GSH with flow control using CV4.

When compared to the discharge variant of the CCGTP with similar equipment, the given parallel circuit theoretically is inferior to it in thermodynamic efficiency due to the relatively smaller ratio of power of the binary vapor-gas cycle, but at the same time it has a number of other practical advantages which results in lower capital costs and higher performance, namely:

- A smaller amount of reconstruction of the steam-power section. In particular, the boiler requires reconstruction of a steam heater due to an increase in steam consumption through it; in the turbine section, the reconstruction and modernization of the flow section of the turbine is necessary;
- Lack of controlled bypassing of GT exhaust gases at part-load operation and, as a result, the absence of regulating gates in gas ducts between GT and boiler;
- No restrictions on gas temperature and oxygen content at the GT exhaust and the corresponding possibility of using high-temperature GTP, as well as the possibility of using this scheme for addition of units to the coal-fired steam boiler.

When steam-power section is included into the combined-cycle power unit, the parameters of water and steam in the thermal scheme of STP change. The steam produced by waste heat recovery boiler is supplied to live steam line in front of high-pressure cylinder of the turbine, causing an increased flow through its flow-through part. In addition, due to feed water heating in HPEc, and condensate heating in GCH, partial displacement of steam extraction into HPH and LPH occurs. This increases vapor pressure in regenerative extractions, extraction at turbo drive and in condenser.

Figure 2 shows the calculated thermal scheme of WHRB with designations of the main parameters.

![Figure 2. Calculated thermal scheme of WHRB.](image-url)

Joint heat balance of HRH and HPEc is:
From this equation we find the expression for consumption of steam produced by WHRB:

\[ G_{WHRB} = G_G \left( h_{1G}^{GSH} - h_{2G}^{E} \right) + G_{HPH} \left( h_0 - h_{1E} \right) - G_{HPH} \left( h_0 - h_{1E} \right) \]

The obtained dependence shows that the steam capacity of WHRB is determined by the flow rate of feed water supplied to the HPH and its heating in HPEc. The flow of feed water in HPH is equal to the steam output of the main boiler and this value can be taken constant. In this case the steam consumption from WHRB linearly depends on \( h_{2E} \). At various steam consumption, the expression (1) will be:

\[ G_{WHRB} = a_i - b_i h_{2E} \]

where \( a_i, b_i \) are coefficients which depend on water flow through HPH.

The value \( G_{WHRB} \) achieves its maximum in the absence of HPEc. The zero value of WHRB steam production will take place (hypothetically) for the maximum possible heating of feed water in HPEc.

Basing on data from thermal calculations for GSH, HPEc, GCH, and AC, we obtained the general form of the \( Q-t \) diagram of WHRB. Analysis of the \( Q-t \) diagram shows that at GSH a zone of minimum temperature drop (\( \Delta t_{\text{min}} \)) occurs in the zone of the highest heat capacities of water vapor. Here the value \( \Delta t_{\text{min}} \) decreases with increasing steam consumption generated in the GSH. In this regard, the steam generating capacity of the GSH for a given gas turbine parameters is limited by the value of the permissible temperature drop.

3. Results and discussions

The calculations results for various types of equipment show that nominal rated efficiency of a CCGTP power unit with a parallel superimposed unit is 2.5–3.0% higher than that of an autonomous steam power unit. The efficiency increase is a consequence of combination of the steam-power unit and the steam-gas superimposed unit in a single thermal scheme. In this case, the value of the generated additional power is ~ 30% of the initial power of the steam turbine, and its output efficiency is 54–55%.

The steam and gas unit under consideration consists of two power plants: a steam turbine and a gas turbine. The increase in nominal rated efficiency of the power unit is explained by the fact that the binary vapor-gas cycle is much more cost-effective than the steam-turbine cycle. Therefore, when developing a power unit capacity control program at part-load operation, it is necessary to maintain a constant power ratio of the gas turbine cycle in the total power unit capacity or even increase this ratio [15]. The latter can be realized by keeping the power of the GTP at part-load constant, while reducing the power unit capacity by unloading the steam turbine. This program was adopted as the main one when the power unit is operating at part-loads, for brevity we will denote it: \( N_{GT} = \text{const} \).

Carrying out the program \( N_{GT} = \text{const} \) substantially changes the parameters of both parts of the power unit, and to the greater extent this influences the steam turbine part. Steam consumption through the steam turbine is reduced, the degree of crowding out of steam for LPH and HPH increases.

WHRB is characterized by a change in the operating mode of the high pressure economizer (HPEc) and the gas condensate heater (GCH). The mode of operation of the generator - superheater (GSH) varies a little, since the gas parameters in its inlet section and the flow rate of the heated medium (water - steam) is constant. Minor changes in the GSH mode are associated only with changes in water temperature at its inlet.

The operating modes of HPEc and GCH are significantly affected by changes in flow of feed water and, consequently, of condensate through these heat exchangers.
The greatest changes in the regime are characteristic of HPEc, since the entire flow of feed water, which is then sent to the HPH and the GSH passes through it. At the same time, the HPEc mode is characterized by the fact that the temperature and flow rate of gases in its inlet section for gases are constant, as well as the feed water temperature (behind the feed pumps) in the inlet section for water. Changes in water flow affect the temperature of gases and water leaving HPEc. These parameters are connected with water consumption and with each other by complex functional relationships, therefore, to find their values, it is necessary to apply the method of successive approximations.

Temperatures of gases and feed water at the outlet of HPEc increase with decreasing feed water flow through it, the dependencies are nonlinear.

The GCH part-load operation also varies, since in its inlet cross section for gases, the gas temperature will have a value that is not equal to the nominal value. In this regard, it is necessary to change the flow rate of the main condensate through the GCH in order to maintain the flue gas temperature at a nominal value and not to increase the heat losses. The water temperature at the inlet to the GCH is maintained approximately equal to 60 °C due to the mixing of the main condensate streams for LPH1 and LPH2.

4. Conclusions

It was revealed that a steam-gas unit with a parallel superimposed GTP unit can be used for modernization of steam turbine units with a capacity of 200 and 300 MW. The analysis of part-load operation of the combined-cycle gas turbine unit shows that the degree of binarity for steam-gas cycle with a parallel superimposed GTP unit at part-loads increases while carrying out the program NGT = const. And this, in turn, causes an increase in the efficiency of CCGTP with a decrease in its power.

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