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Development of technologies to increase efficiency and reliability of combined cycle power plant with double-pressure heat recovery steam generator

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Abstract. To increase the efficiency of a combined cycle power plant, it was suggested in a double-pressure heat recovery steam generator to carry out a reheat of water steam that had been spent in a high pressure cylinder of a steam turbine. The researchers introduce a mathematical algorithm and calculation methodology of the waste-heat boiler. It is proved that after re-superheat of water vapour in a double-circuit waste-heat boiler after the high-pressure superheater (with vapour already used in the high-pressure cylinder of a condensing steam turbine), a CHP-plant efficiency and reliability increase. Calculations for the combined cycle gas turbine unit PGU-450 were performed. It is shown that when the reheater is installed in the recovery steam generator, its efficiency increases by 2.15%. At the same time the efficiency of CCGT for power generation is increased by 3.36%, the degree of dry water steam used in the turbine is increased by 0.082. Consequently, the specific consumption of conventional fuel for electric power generation is reduced by 6.1%. Re-superheating of the total flow of water vapour allows to increase CGP-450 steam-gas unit efficiency by increasing the parameters of the steam entering the low-pressure cylinder of the steam turbine.

1. Introduction

Thermal efficiency of the combined cycle power plant depends on the degree of perfection of the gas-turbine installation, steam turbine and recovery steam generator [1]. Significant reserves in increasing the efficiency of the recycling CCGTU are laid down in the improvement of the steam cycle, which, as is known, provides about 1/3 of the power of the CCGTU [2]. The efficiency of the CCGTU-U is greatly influenced by the efficiency of the recovery steam generator, which depends not only on the temperature of the exhaust gases at the outlet of its convoy shaft, but also on the temperature of the ambient air [3]. One of the ways to increase efficiency of the recovery steam generator and economy of the recovery-type CCGTU is to increase the number of convective surfaces of RSG heating in order to reduce the rate of exhaust gases of GTI.

The purpose of the work is to develop technologies to increase the efficiency [4] and reliability [5] of the combined cycle power plant with a double-pressure heat recovery steam generator due to the use of intermediate reheater of water steam used in the high-pressure cylinder of the steam turbine [6].

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2. Materials and Methods

In order to increase the economy and reliability of the combined cycle gas turbine unit operation PGU-450 is proposed to place the reheater of water steam [7] partially used in the high-pressure cylinder of the steam turbine (figure 1) in a double-pressure heat recovery steam generator.

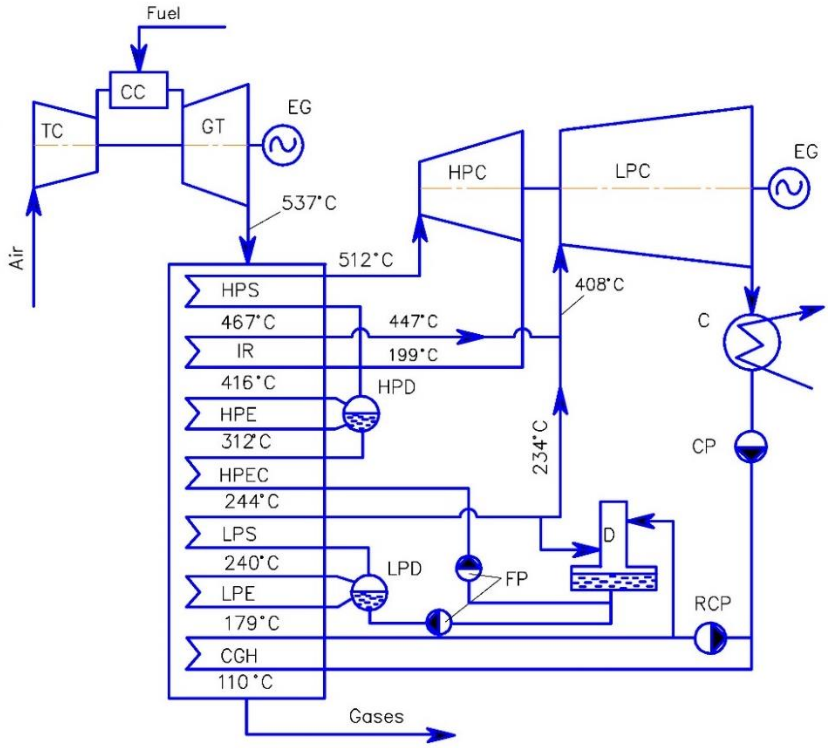

Figure 1. Thermal schematic diagram of CCGTU-U with reheat of steam in recovery steam generator.

The considered unit of the PGU-450 includes: Siemens V94.2 gas turbine installation with nominal capacity of 155 MW, two-pressure recovery steam generator P-90 with forced circus of working medium in high and low pressure evaporation circuits and steam turbine condensing plant KT-150-8. Design electric power of PGU-450 in nominal mode at operation without reheat of water steam is 460.44 MW, and its efficiency is 51.76%.

To determine efficiency of using secondary superheat [8] of water steam in CCGT with double-pressure heat recovery steam generator, single reheat is considered with arrangement of heating surface of reheater in zone of high temperatures of recovery steam generator downstream of main superheater of high pressure [9]. The double-pressure heat recovery steam generator P-90 includes the following heat exchange surfaces: high and low pressure superheaters (HPS, LPS), intermediate reheater (IR); high and low pressure evaporator (HPE and LPE); high pressure economizer (HPEC); condensate gas heater (CGH).

The heat scheme of the PGU-450 was calculated and the economic parameters of its operation were determined [10]. Calculations are performed for two components: 1) during CCGTU operation without intermediate reheat; 2) during CCGTU operation with reheat of water steam. The methodology described in is adopted as the basis. The results of the calculations are shown in figure 2, 3.

From the equations of thermal balance for the heating surfaces of the heat recovery steam generator, the enthalpies of gases after the superheaters (HPS, LPS, IR), evaporator (HPE and LPE), economizer (HPEC) and condensate gas heater (CGH) were calculated.

Enthalpies of gases:

after superheaters of high and low pressure

$$h''_{hps} = h'_{rsg} - D_0^{hp}(h_0^{hp} - h''_{s(hp)})/G_g\ ; \tag{1}$$

$$h''_{lps} = h''_{hpec} - D_0^{lp}(h_0^{lp} - h''_{s(lp)})/G_g\ ; \tag{2}$$

after superheaters of high and low pressure

$$h''_{ir} = h''_{hps} - D_0^{hp}(h''_{ir} - h'_{ir})/G_g\ ; \tag{3}$$

downstream of high pressure water economizer

$$h''_{hpec} = h''_{hpe} - D_0^{hp}(h_1 - h_d^{hp})/G_g\ ; \tag{4}$$

at condensate gas heater outlet

$$h''_{rsg} = h''_{lpe} - G_{cgh}(h''_c - h'_c)/G_g\ , \tag{5}$$

where h''_{hps}, h''_{lps}, h''_{ir}, h''_{hpec}, h''_{rsg}, h'_{rsg} – enthalpy of gases after high and low pressure superheaters, intermediate reheater, high pressure economizer, condensate gas heater, enthalpy of gases at heat recovery steam generator inlet respectively; h_0^{hp}, h_0^{lp} – high and low pressure superheated steam enthalpy; $h''_{s(hp)}$, $h''_{s(lp)}$ – enthalpy of water steam at saturation temperature in the drum of you-well and low pressure; h'_{ss}, h''_{ss} – enthalpy of superheated water steam at the inlet of the intermediate reheater and at the outlet of it; G_g – mass flow rate of gases entering the heat recovery steam generator; h_1 – enthalpy of feedwater entering the high pressure drum; h_d^{hp} – enthalpy of feedwater entering the HPEC; h'_c, h''_c – enthalpy of water at CGH inlet and outlet; h''_{hpe}, h''_{lpe} – enthalpy of gases after high and low pressure evaporator; D_0^{hp} and D_0^{lp} – high and low pressure steam flow rates; $G_{cgh} = D_0^{hp} + D_0^{lp} - D_d + G_r$ – water flow rate through condensate gas heater; D_d and G_r – steam consumption for deaerator and water for recirculation.

From the thermal balance equations for each evaporator, high and low pressure steam flow rates were determined:

$$D_0^{hp} = \frac{G_g(h''_{ir} - h''_{hpe})}{h''_{s(hp)} - h_1}; \tag{6}$$

$$D_0^{lp} = \frac{G_g(h''_{lps} - h''_{lpe})}{h''_{s(lp)} - h_d^{lp}}. \tag{7}$$

h_d^{lp} – low pressure circuit feedwater enthalpy.

Steam flow to deaerator:

$$D_d = \left(D_0^{hp} + D_0^{lp}\right)\left(h_d - h''_c\right)/\left(h_0^{lp} - h''_c\right), \tag{8}$$

h_d – enthalpy of water after deaerator.

Condensate flow for recirculation to increase water temperature before CGH:

$$G_r = \left(D_0^{hp} + D_0^{lp} - D_d\right)\left(h'_c - h_{cp}\right)/\left(h''_c - h'_c\right). \tag{9}$$

h_{cp} – condensate enthalpy downstream of condensate pump.

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Mass flow rate of exhaust gases of GTI G_g = 506.15 kg/s, air excess factor α = 3.33 was calculated according to formulas given in. By enthalpy of gases at condensate gas heater outlet temperature of gases at heat recovery steam generator t''_{rsg}. outlet is determined.

The efficiency of the heat recovery steam generator is determined by the ratio of the difference of enthalpies of gases at the inlet of the control unit and at the outlet of its convective shaft to the difference of enthalpies of gases at the inlet of the control unit and enthalpies of gases discharged into the environment, cooled in the atmosphere to the ambient air temperature:

$$\eta_{rsg} = \left(h'_{rsg}\text{-}h''_{rsg}\right) / \left(h'_{rsg}\text{-}h_{at}\right). \tag{10}$$

To find of gas temperature after high and low pressure evaporator, the values of temperature pressures at pinch points of HPE and LPE - δt_s^{hp} = 8 °C, δt_s^{lp} = 7 °C were accepted. The temperature of the gases after each evaporator was determined from the saturation temperature in the drum and the accepted temperature head:

$$\theta_s^{hp} = t_s^{hp} + \delta t_s^{hp}; \theta_s^{lp} = t_s^{lp} + \delta t_s^{lp}. \tag{11}$$

In figure 2, the process of superheating in the intermediate reheater installed after the superheater with a high pressure line.

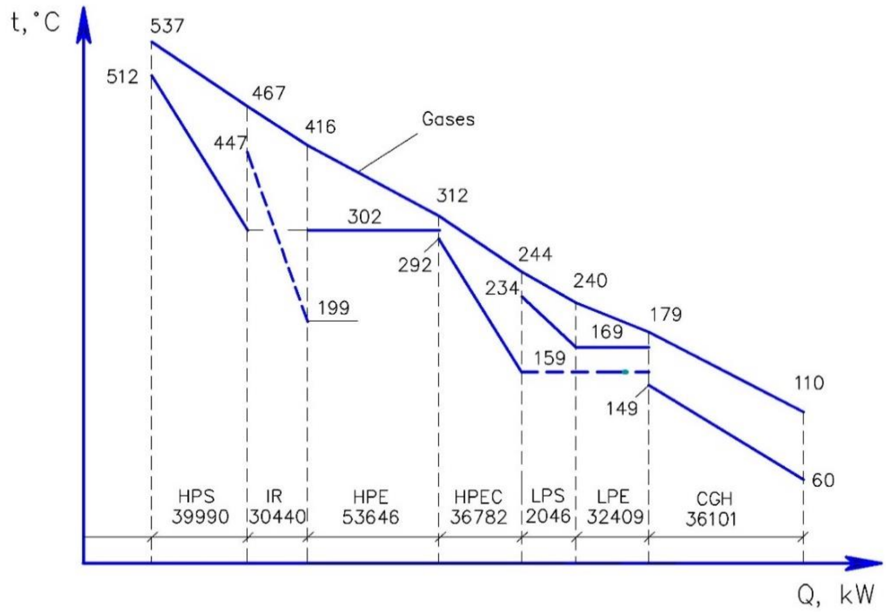

Figure 2. Heat diagram of the heat recovery steam generator P-90 with arrangement of reheater after the superheater of high pressure.

Figure 3 shows the process of water steam expansion in a steam non-reheat turbine. Figure 4 shows the process of water steam expansion in steam turbine at single intermediate reheat of water steam in heat recovery steam generator with arrangement of intermediate reheater downstream of high-pressure superheater along the flow of outgoing combustion products [11].

Steam enthalpy in the mixing camera at implementation of intermediate reheat of water steam in a zone of high temperatures of the heat recovery steam generator was determined by a formula:

$$h_{\text{mix}} = \left[D_0^{hp} h''_{ss} + \left(D_0^{lp} - D_d\right) h_0^{lp}\right] / \left(D_0^{hp} + D_0^{lp} - D_d\right). \tag{12}$$

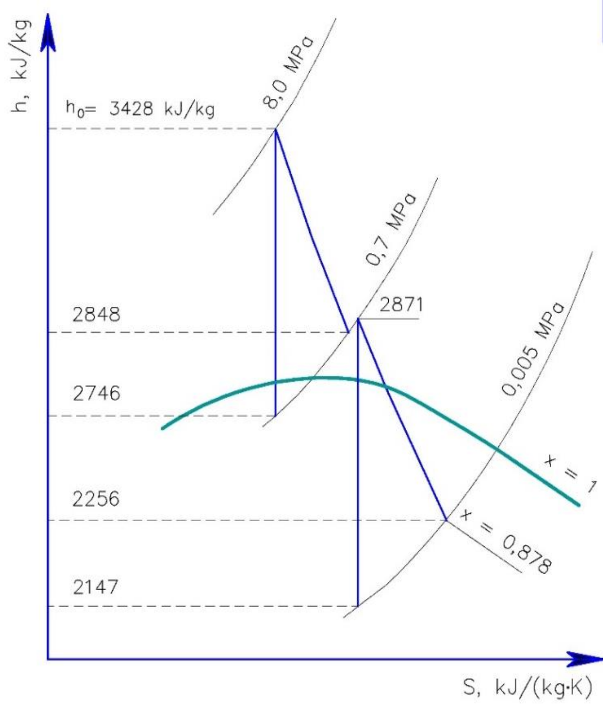

Figure 3. Steam expansion process for turbine KT-150-8 in case of single-stage intermediate reheat in heat recovery steam generator.

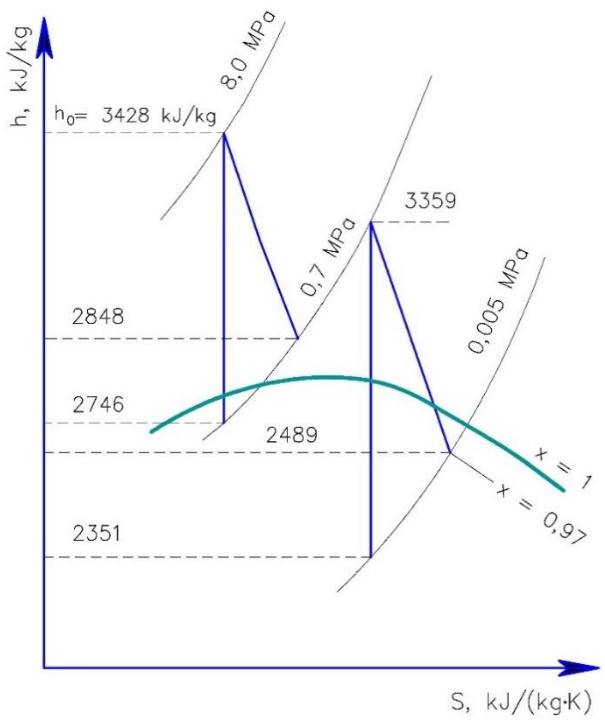

Figure 4. Process of expansion of water steam for turbine KT-150-8 at single re-heat of steam in heat recovery steam generator.

3. Results

Calculations for the technical specifications of the PGU-450 were performed with the following initial data: p_0 = 8.0 MPa; Pc = 5 kPa; Rd = 0.6 MPa; Ne = 155.3 MW; steam pressure of a contour of low pressure of – 0.7 MPa; electric efficiency of GTI – 0.344; gas temperature on an entrance to a heat recovery steam generator – 537 °C. The calculation results of the main technical and economic indicators of CGP-450 with the use of water vapour re-superheat in the waste-heat boiler and without its use are given in Table 1.

Table 1. The calculation results of PGU-450 operation with the use of water vapour resuperheat in the waste-heat boiler and without its use.

Parameter	Parameter point Without intermediate reheat	 With reheat of water steam
Electric power of GTI, MW	155.27	155.27
Electric efficiency of GTI, %	34.4	34.4
Electric power of STP, MW	149.9	178.86
Electric efficiency of STP, %	33.21	38.59
Efficiency RSG, %	79.71	81.86
Electric power of CCGTU, MW	460.44	489.4
Electric efficiency of CCGTU, %	51.76	55.12
Steam properties high pressure loop		
– pressure, MPa	8.0	8.0
– temperature, °C	512	512
– flow, t/h	198.29	198.29
Steam properties after intermediate reheater:		
– pressure, MPa	–	0.6
– temperature, °C	–	464
– flow, t/h	–	198.29
Steam properties in the steam turbine mixing chamber:		
– pressure, MPa	0.7	0.7
– temperature, °C	203	408
– flow, t/h	396.58	396.58
Steam properties low pressure loop:		
– pressure, MPa	0.7	0.7
– temperature, °C	245.0	234.0
– flow, t/h	64.43	64.43
Gas temperature of the heating surfaces of the heat recovery steam generator. °C:		
–after GTU	537	537
–after HPS (base and intermediate)	467	467
–after intermediate reheater	–	416
–after HPE	327	312
–after HPEC	265	244
–after LPS	259	240
–after LPE	194	179
–after CGH	122	110
Specific consumption of conventional fuel, g/kWh	237.64	223.15

4. Conclusion

The heat scheme of the PGU-450 was calculated for two versions of operation: without performing intermediate reheat and with performing intermediate reheat of steam used in the high-pressure cylinder of the steam turbine [12]. When performing the intermediate reheat of the water steam in the heat recovery steam generator. the main characteristics of the CCGTU increase: electric power from 460.44 to 489.4 MW (by 28.96 MW). efficiency of power generation from 51.76 to 55.12% (by 3.36%) and the degree of dryness of the waste water steam in the turbine from 0.877 to 0.959 (by 0.082). Accordingly. the specific consumption of conventional fuel on the electric power supply is reduced from

237.64 to 223.15 g/kWh (by 6.1%) [13]. At the same time. saving of conventional fuel for PGU-450 at its operating time of 4500 hours per year and cost of conventional fuel of 3700 rubles/t. In monetary terms is 118.72 million rubles/year. Analysis [14] of the calculation results indicates that when the intermediate reheater is installed in the heat recovery steam generator after the superheater of high pressure. the efficiency of the CCGTU operation is substantially increased [15].

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