Economic assessment of the use of double-acting resuperheating of water vapor at the PGU-420 Cherepovets state district power station

A A Kudinov, S K Ziganshina and K R Khusainov

Samara State Technical University, ul. Molodogvadreiskaya 244, Samara, 443100, Russian Federation

E-mail: tes@samgtu.ru

Abstract. To increase the efficiency of a three-circuit combined-cycle plant, it is proposed to perform double resuperheating of water vapor in the high pressure loop (intermediate superheater ISH-1) and in the cooler part of the heat recovery boiler (intermediate superheater ISH-2). It was found by calculation that the implementation of the double reheated steam at high pressure and the tail of the WHRB increases the electrical efficiency of PGU-420 by 0.92% compared to the option of a single resuperheat (from 60.45 to 61.37%). The capacity of PGU-420 increases by 3.7% (from 422.94 to 438.61 MWt). The specific reference fuel consumption is reduced by 1.5% (from 203.47 to 200.42 g/(kWt·h)). The steam dryness factor increases by 6.03% (from 93.2 to 99.23%). The steam turbine efficiency increases by 1.15% (from 36.26 to 37.41%), and steam turbine power increases by 11.61% (from 134.94 to 150.61 MWt). The economic effect of the implementation of the second water vapor resuperheating in monetary terms is 48.0 million rubles per year when the cost of fuel equivalent is 3700 rubles/t. f. e. and at the operating time of 7500 h/year.

1. Introduction
Currently, binary combined-cycle plant (CCP) are the most promising from the point of view of thermal efficiency, it includes a gas turbine unit (GTU), a waste heat recovery boiler (WHRB) and a steam turbine, the unit operate on a combined Brighton-Rankin cycle. CCP accounts for approximately 35% of the total volume of new capacity recently introduced at thermal power plants. [2, 8, 9]. Modern CCP have a high efficiency of electric power output (at least 50%), low cooling water consumption compared to steam-turbine units of the same capacity, and low emissions of harmful substances. Natural gas is used as the main type of fuel in combined-cycle gas utilization plants (CCP-U). The share of natural gas in the Russian fuel balance exceeds 60% [1, 2].

The list of priority tasks for the development of combined steam and gas units includes increasing the thermal efficiency of steam turbines, the efficiency of which does not exceed 36% due to reduced initial parameters of water vapor and the lack of a regenerative heating system for turbine condensate and feed water [1, 2, 9]. In this case, the useful use problem of the heat of the exhaust gases of GTU becomes relevant not only for the production of superheated water vapor in the boiler, but also for its resuperheating. The use of the water vapor resuperheating allows to increase the thermal efficiency and reliability of the steam turbine by supplying additional heat to the working body and reducing the final moisture content (increasing the dryness factor) of the steam. In doing so, the efficiency of WHRB increases as a result of deeper cooling of the exhaust gases [2, 5].
The water vapor resuperheating is used mainly on powerful CCP with three-circuit WHRB. These installations include a single-stage combined-cycle gas plant with a capacity of 420 MWt (PGU-420) that was put into operation at Cherepovets SDPS.

The PGU-420 consists of one Siemens SGT5-4000F gas turbine unit with a nominal capacity of 288 MW, an EMA-29-KU three-pressure WHRB, and a Siemens SST5-3000 condensing steam turbine. The estimated electric power of the PGU-420 is 423 MWt, and its efficiency is 60.45 % when working with a single resuperheating of water vapor.

2. Experimental
To increase the efficiency of a three-circuit CCP, it is proposed to perform double resuperheating of water vapor in the high pressure loop (resuperheater ISH-1) and in the cooler part of the heat recovery boiler (resuperheater ISH-2) (figure 1).

Figure 1. Thermal scheme of the PGU-420 Cherepovets SDPS with double resuperheating of water vapor in the recovery boiler

The combined-cycle plant works as follows. The heat of GTU exhaust gases is usefully used in a three-circuit WHRB for heating water, generating and superheating water vapor.

A special feature of the presented thermal scheme is that the flow of exhaust gases of the gas turbine unit is divided into two streams after the condensate gas heater (CGH) of WHRB. A smaller flow of exhaust gases of the gas turbine unit with a flow rate $G_{g2}$ is an oxidizing medium for the fuel combustion process in the chamber of supplementary firing fuel (CSFF), behind which the heat exchange surface of the second resuperheater is located ISH-2. After CGH, the main flow of exhaust GTU gases with the flow rate $G_{g1}$ is mixed with the gases that were spent in ISH-2. After mixing the two streams, the total flow of exhaust gases in the design mode at a temperature of 120 °C is diverted to the chimney.

Water vapor is superheated in the main superheater (HPSH), fed to the high-pressure cylinder (HPC) of the steam turbine, where it expands and performs useful work. Water vapor returns to WHRB after HPC, reheated again to a temperature of 560 °C in the first stage resuperheater (ISH-1), and then mixed with the steam flow of medium parameters and enters the first part of the middle pressure cylinder (MPC-1) steam turbine. The total flow of water vapor is expanded in the MPC-1 to a pressure of 1.2 MPa, after which it is re-selected for secondary superheating to 560 °C in the second stage (ISH-2), of the resuperheater. A secondarily superheated water vapor is fed to the second part of...
the medium-pressure cylinder MPC-2, where it performs work. After the MPC-2, the water vapor stream is mixed with the steam superheated in a low-pressure superheater and sent to the low pressure cylinder (LPC) of the steam turbine, where the expansion process is completed.

To determine the effectiveness of using the double resuperheat steam, a comparative analysis of the PGU-420 operation with a single and double resuperheating of steam in the recovery boiler was performed according to the method described in [3, 7].

According to the heat balance equation for the main and intermediate superheaters located in parallel, the enthalpy of gases at the exit from these heating surfaces is determined:

\[ h_{mix1} = \frac{D_0^{hp} h_{hp} + D_0^{mp} h_{mp}}{D_0^{mp} + D_0^{hp}} \]

(2)

Here: \( D_0^{hp}, D_0^{mp} \) – flow rates of superheated steam of high parameters and exhaust gases of GTU, kg/s; \( h_{hp}, h_{mp} \) – enthalpy of superheated and saturated high-pressure water vapor., kJ/kg; \( h_{mix1}, h_{mix2} \) – the enthalpy of the steam mixture at the entrance to the first stage of the resuperheater and at the exit from it. \( D_0^{hp} \) is determined by the method of successive approximations.

In the above formula, the enthalpy of the steam mixture at the entrance to the first stage of the intermediate superheater is determined by the formula:

\[ h_{mix2} = \frac{(D_0^{hp} + D_0^{mp}) h_{mpc-2} + D_0^{lp} h_{lp}}{D_0^{hp} + D_0^{mp} + D_0^{lp}} \]

(4)

Here: \( D_0^{lp}, h_{lp} \) – flow rate and enthalpy of superheated low-pressure water vapor.

The internal capacity steam turbine cylinders:

\[ N_i^{hp} = D_0^{hp} \cdot H_i^{hp}; \]

(5)

\[ N_i^{mpc-1} = (D_0^{hp} + D_0^{mp}) \cdot H_i^{mpc-1}; \]

(6)

\[ N_i^{mpc-2} = (D_0^{hp} + D_0^{mp}) \cdot H_i^{mpc-2}; \]

(7)

\[ N_i^{lp} = (D_0^{hp} + D_0^{mp} + D_0^{lp}) \cdot H_i^{lp}; \]

(8)

где \( H_i^{hp} = h_{hp} - h_{mix1}, H_i^{mpc-1} = h_{ish-1} - h_{mpc-1}, H_i^{mpc-2} = h_{ish-2} - h_{mpc-2}, H_i^{lp} = h_{mix2} - h_{lp} \)

– heat drop of water vapor in the turbine cylinders, kJ/kg; \( h_{hp}, h_{mpc-1}, h_{mpc-2}, h_{lp} \) – the enthalpy of spent steam at the outlet of the turbine’s HPC, MPC-1, MPC-2, and LPC, respectively.

The electric power of a steam turbine is determined by the sum of the internal capacities of the cylinders \( N_i \), taking into account the electromechanical efficiency \( \eta_{em} \):

\[ N_{et} = (N_i^{hp} + N_i^{mpc-1} + N_i^{mpc-2} + N_i^{lp}) \cdot \eta_{em}. \]

(9)

The efficiency of a combined-cycle plant is determined by the formula:
\[ \eta_{pgu} = \frac{N_{gtu} + N_{st}}{B_{cc}Q_{cc}^w + B_{afcc}Q_{cc}^w}, \]  

here \( B_{cc}, B_{afcc} = \frac{g_{g2}(h_{ish-2}' - h_{ish-2}' - h_{ish-2}'') - g_{g2}h_{gch}}{Q_{cc}^w} \) – fuel consumption in the combustion chamber of the GTU and in the CSFF of the recovery boiler, kg/s.; \( Q_{cc}^w \) – low heat value, kJ; \( G_{g2}, h_{ish-2}', h_{ish-2}' \) – flow and enthalpy of gases before the second stage of the resuperheater and at the exit from it.

3. Results and Discussions
Figure 2 shows a thermal diagram of a three-circuit heat recovery boiler based on the results of a thermal calculation, with a single and double resuperheating of water vapor. Water vapor is superheated from 359 \(^\circ\)C to 560 \(^\circ\)C in ISH-1, and water vapor is superheated from 427 \(^\circ\)C to 560 \(^\circ\)C in ISH-2. Figure 3 shows \( h, s \) – diagrams of water vapor expansion processes in a turbine with a single and double steam resuperheating of water vapor.

3. Results and Discussions
Figure 2 shows a thermal diagram of a three-circuit heat recovery boiler based on the results of a thermal calculation, with a single and double resuperheating of water vapor. Water vapor is superheated from 359 \(^\circ\)C to 560 \(^\circ\)C in ISH-1, and water vapor is superheated from 427 \(^\circ\)C to 560 \(^\circ\)C in ISH-2. Figure 3 shows \( h, s \) – diagrams of water vapor expansion processes in a turbine with a single and double steam resuperheating of water vapor.

**Figure 2.** Thermal diagram of a three-circuit heat recovery boiler with intermediate superheating of water vapor: \( t \) – temperature, \( Q \) – heat output

**Figure 3.** Comparison of steam expansion processes in a turbine with a single (a) and double (b) resuperheating of water vapor in the WHRB
For $Q_l^{c}=53820$ kJ/kg, $B_{cc}=13.0$ kg/s, $B_{afcc}=0.035$ kg/s. The efficiency of WHRB is: $\eta_{ku}= (h_{gt}' - h_{ku}') / (h_{gt}' - h_{oa}) = 0.8547$, $\eta_{pgu} = 0.6045$ and $\eta_{pfgu} = 0.6137$, respectively, for the case of operation of the unit with a single and double intermediate superheating of water vapor in the WHRB.

4. Conclusion

1. It is proposed to place a special gas flue in the tail of the waste heat boiler, in which the KDST and the heat exchange surface of the second intermediate superheater are installed sequentially along the gas flow, which allows the total flow of outgoing gas from the gas turbine to be divided into two streams, the smaller of which is an oxide medium for the fuel combustion process Gorenje in the KDST.

2. It was found by calculation that the implementation of the double reheated steam at high pressure and the tail of the WHRB increases the electrical efficiency of PGU-420 by 0.92 % compared to the option of a single resuperheat (from 60.45 to 61.37 %). The capacity of PGU-420 increases by 3.7 % (from 422.94 to 438.61 MWt). The specific reference fuel consumption is reduced by 1.5 % (from 203.47 to 200.42 g/(kWt·h)). The steam dryness factor increases by 6.03 % (from 93.2 to 99.23 %). The steam turbine efficiency increases by 1.15 % (from 36.26 to 37.41 %), and steam turbine power increases by 11.61 % (from 134.94 to 150.61 MWt). The economic effect of the implementation of the second water vapor resuperheating in monetary terms is 48.0 million rubles per year when the cost of fuel equivalent is 3700 rubles/t. f. e. and at the operating time of 7500 h/year.

References

[1] Burov V D, Dorokhov E V, Elizarov D P et al 2005 Thermal Power Plants: Textbook for Universities (Moscow: MPEI) p 454
[2] Kudinov A A 2012 Thermal Power Station. Schemes and Equipment: Studies. The Manual for High Schools (Moscow: INFRA-M) p 325
[3] Kudinov A A and Ziganshina S K 2019 Steam-gas Installations of Thermal Power Plants: Textbook. The Manual for high schools (Samara: Samar. state tech. UN-t) p 230
[4] Kudinov A A and Ziganshina S K 2011 Energy Saving in Heat Power Engineering and Heat Technologies (Moscow: Mechanical Engineering) p 374
[5] Moshkarin A V, Devochkin M A, Shelygin B L and Rabenko V S 2002 Analysis of Trends in the Development of Domestic Energy (Ivanovo: IG-EU) p 256
[6] Truini A D 201) Combined-cycle Plants of Power Stations: proc. the manual for high schools (Moscow: Publishing house MEI) p 648
[7] Truini A D and Romanuk A A 2006 Calculation of thermal schemes for utilization of steam and gas installations (Moscow: MPEI Publishing house) p 40
[8] Usov S V and Kudinov A A 2013 Analysis of technical and economic indicators of Syzran power plant after its modernization with the installation of CCGT-200 Energetik 12 43–5
[9] Tsanev S V, Burov V D and Remezov A N 2009 Gas-turbine and Steam-gas Installations of Thermal Power Plants: Textbook. The manual for high schools (Moscow: MPEI Publishing house) p 584