Problems of energy and resource efficiency in heat and power engineering: water treatment

E.N. Bushuev¹, B.M. Larin¹, E.A. Karpychev¹

¹Ivanovo State Power Engineering University, 153003, Russian Federation, Ivanovo, Rabfakovskaya St., 34
admin@xxte.ispu.ru

Abstract. An analysis is submitted of the main developments in energy and resource efficiency both in currently operating water treatment systems and those being put into service. A big potential for energy efficiency exists in reverse osmosis installations regarding reduced source water consumption and also disposal of concentrate forming in the water treatment system cycle. A promising development in energy saving is reducing the temperature of raw water warming.

1. Energy and resource efficiency at thermal power plants (TPP)

The principal aim of energy and resource efficiency at currently operating thermal power plants is to reduce specific fuel consumption. This is often accompanied by measures to reduce operating costs, including those relating to repairs and operating personnel. The purpose of such measures is usually to increase the profitability of a power generating facility.

Modern heat and power engineering development is moving towards increased thermodynamic cycle efficiency both by changing over to binary (double) cycles in combined cycle gas turbine (CCGT), and by increasing the initial parameters of main steam in once-through ultra supercritical (USC) boilers using solid fuel.

Increased power generation unit efficiency is achieved by improving the thermodynamic cycle, optimizing plant cycle, improving main and auxiliary equipment and raising turbine inlet steam parameters. Table 1 shows data for possible increased efficiency with increased thermodynamic cycle parameters.

The problems of heat engineering development in this direction are related to the need for close coordination and control in the operation of different kinds of equipment (combined cycle units), construction materials, developed heat exchange surfaces, water quality (USC and CCGT units).

The potential for improved energy efficiency at coal-burning condensation power plants may be related to changing over to new steam turbine plants with ultra supercritical steam parameters. Under the leading role of the All-Russian Heat Engineering Institute (AHEI), a 600MW power generation unit was developed in 2007-2008 with a once-through boiler operating on Kuzbas grades G and D bituminous coal at 28.4 MPa (Pp-1860-28,4-600 CS). Boiler outlet steam parameters meet the following conditions: pressure – 28.4 MPa, temperature – 600 °C [2]. Calculated analysis was performed for once-through overheating boiler operation (Pp-1000-25-585) with circulating boiling layer and oxyfuel firing, and the possibility of using this boiler in big coal-fired power generation units with USC once-through boilers was demonstrated [3]. Data from the Russian Central Engineering Research Institute (CERI) are given for new heat resistant chrome steel grades 12KH10M1V1MFBR
and 10KH9V2MFBR for turbine rotors, boiler piping, and steam piping for USC power generation units implemented in Russian industry [4]. With parameters increased from standard \( p_0 = 25 \text{ MPa}, t_0 = 545^\circ \text{C} \) to \( p_0 = 30 \text{ MPa}, t_0 = 700^\circ \text{C} \), power generation efficiency is increased by approximately 45%. Plant cycle optimization and improvements in main and auxiliary equipment allow a further 2.4% increase in efficiency.

**Table 1. Potential for improving thermodynamic cycle parameters [1]**

| Measure                                      | Increase in efficiency, % |
|----------------------------------------------|----------------------------|
| Increasing main steam temperature by 1 °C    | 0.02                       |
| Increasing main steam pressure by 1 MPa      | 0.1                        |
| Increasing re-superheating temperature by 1 °C| 0.015                     |
| Using second re-superheating                 | 1.2                        |
| Lowering condensate pressure by 1 kPa        | 1                          |
| Increasing feed water temperature by 1°C     | 0.02                       |

At present, highly maneuverable combined cycle power generation units burning natural gas with efficiency of more than 55-57% are widely used. Apart from improved economic indicators in power generation, increased power plant efficiency is one of the principal ways to reduce harmful atmospheric emissions.

2. **Energy and resource efficiency in water treatment systems**

The tasks of achieving energy and resource efficiency in water treatment, cooling and water-chemical regime systems in heat power equipment main and auxiliary circuits at thermal power stations are always relevant, and increasingly so with growing electric and heat power consumption. The problems of fulfilling these tasks are related to the need to ensure standard water quality with limited discharge of waste water, and in the final analysis are determined by the cost of technological measures.

Water treatment plant (WTP) at thermal power plants in an overwhelming majority of cases are represented by traditional installations for pretreatment (clarifiers and mechanical filters) and ion exchange filters (softening and demineralization). The last 10 years have seen the active introduction of reverse osmosis systems (ROS) at thermal power plants, usually, however, with the retention of ion exchange filters.

Energy efficiency for water treatment facilities at thermal power plants is determined by reducing own electric power consumption and heat consumption for source water heating. Electric power consumption may be reduced by adjusting design, for example, by reducing the number of high output pumps and providing their electric motors with frequency drives. The number of operating pumps may be reduced, for example, by bypassing decarbonizers in water demineralization circuits with filter chains during lime softening of water in clarifiers. Heat energy consumption may also be reduced by adjusting design. Thus, in some cases source water for WTP is drawn from the return line of circulating water piping, that is, steam turbine condensate cooling system. At some thermal power plants, the condensers are provided with «built in» loops, ensuring independent source water heating with heat from steam condensation. Moreover, in all these cases reduced water consumption for own needs and wastewater flow in WTP leads to reduced wastewater losses.

The problems of implementing the above and other energy efficiency measures are usually related to the need to change (complicate) the technological designs of currently operating equipment, sometimes with the necessity of installing automatic process monitoring (including chemical) and control.

The main criteria regarding the choice of water demineralization processes are economic. A comparison of demineralization operating costs demonstrates the advantage of chemical methods – ion exchange at strong acid anion concentrations ([Cl⁻]+[SO₄²⁻]) of less than 3 mmol/l [5]. Such low mineralized water predominates in Russia’s central and northern regions.
In addition to developing promising water treatment technologies for thermal power plants, it is also necessary to achieve the highest possible indicators for currently operating natural water demineralizers. Energy and resource efficiency with traditional chemical demineralizers may be achieved by implementing the following measures [6]:

- stepwise regeneration of first stage H-cation exchange filters with increasing sulfuric acid concentration;
- regeneration of second stage OH-anion exchange filters with 6-12 hour maturation of NaOH solution in the filter after passing 65–70 % of working fluid volume;
- periodic chemical treatment of anion exchange in first stage filters by saline-alkaline or acidic-saline regeneration.

Changing over to promising ion exchange technologies in express (high velocity) filters ensures energy and resource efficiency, but requires thorough automated monitoring and control of equipment operation.

Membrane water treatment technologies have significant advantages over ion exchange according to environmental indicators (Fig. 1), but require more thorough water pretreatment.

Fig. 1. Relative salt discharge without taking into account salt discharge from water supplied with source water ($\Delta g_{so}$) depending on method of desalting and mineralizing source water: 1 – chemical desalting based on countercurrent ion exchange filters; 2 – desalting based on reverse osmosis with further desalting in ion exchange filters

Water treatment systems based on membrane technologies are characterized by high consumption of waste water (up to 50% of system capacity).

Reverse osmosis systems have big resource efficiency potential and possibilities for lower source water requirements, also disposal of concentrates forming in the water treatment cycle. Using a number of design adjustments for reverse osmosis systems, such as multicascade and mixing of water flows, permits a reduction in own requirements (up to 30%) with negligible deterioration in the quality of the resulting permeate [7, 8]. Reduced consumption of concentrates leads to reduced concomitant heat loss.

A number of design adjustments are proposed, envisaging partial softening of reverse osmosis system concentrate in an H-carboxyl filter [9]. The performed calculations show that using the proposed technologies enables up to 80% of concentrate to be returned to the system inlet. Adding processed concentrate to ROS source water reduces the likelihood of carbonate deposits forming on the membrane, enabling us to simplify, and often dispense with source water treatment.
Processed concentrate may also be used for other purposes, for example, after softening in a carboxyl H-cation exchanger and decarbonization to replenish the heating system.

Regeneration of a H-carboxyl cation exchanger is performed by stoichiometric consumption of sulfuric acid. The resulting discharge is diverted into a gypsum crystallizer; the resulting precipitate may be dehydrated at a slime compacting station. The product obtained in this way meets the material requirements for gypsum binding substances.

One of the important issues to be resolved in the design and operation of reverse osmosis systems is choosing a rational treatment of source water to prevent the formation of sediment on membrane surfaces. For this purpose, the following methods of treating source water are commonly used [7]:

- acidification;
- softening with ion exchange (Na-cation exchange or H-carboxyl) filters;
- addition of antiscalant;
- nano-filtration.

Fig. 2 shows the estimated relation between consumption of reagents to achieve a Langelier index (LSI) of not more than 0.7 and the degree of source water concentration at reverse osmosis system inlet, with various kinds of source water pretreatment. The resulting increased quantity of discharged salts is shown in Fig. 3.

Analysis of the results of numeric study (examination) shows maximum consumption and thus maximum quantity of discharged salts occur with Na-cation exchange, although this is the most reliable method of preventing the formation of harness cation deposits on membrane surfaces. The least consumption of reagents occurs when water is treated with antiscalant. The toxicity of these substances during discharge of reverse osmosis system concentrate should be borne in mind, however.

An important energy efficiency issue in water treatment systems is the possibility of lowering the temperature at which source water is heated.

This temperature may be lowered by using flocculants at the pretreatment stage. These are already being used at most of water treatment systems, with, however, “out of date” polyacrylamide (PAA) or other flocculants that do not always achieve the required results.
Fig. 3. Dependence of daily discharged ions on permeate concentration (Kк) and discharge (water efficiency η) and type of source water treatment at reverse osmosis system inlet:

1 – acidification with sulfuric acid; 2 – Na-cation exchange; 3 – addition of antiscalant; 4 – nano-filtering

Inadequate efficiency of flocculants may be due to the following causes: improper preparation, storage and transportation of flocculants; bad choice of points for reagent entry; inadequate flocculant mixing; unsuitability of flocculant grade for clarifier hydraulic and slime modes; excessive heating of source water (not related to lime softening modes).

Heating source water to above 25 °С does not always have a positive effect for coagulation modes. On the one hand, source water temperatures of 25 °С and higher permit faster hydrolysis of coagulants and lower water viscosity, but on the other hand intensify the process of gas formation.

There is the notion of «cold coagulation», which presupposes heating water to a significantly lower temperature, even to the point of treating the water without preheating. This permits not only lower thermal energy costs, but also improved hydraulic characteristics for slime in relation to its flocculence actually in the clarifier. For example, rapid hydrolysis may result in the formation of heavy slime, containing in its structure huge quantities of microbubbles, mainly CO₂. Using flocculants in this mode permits concentration of the slime into large objects with a significant surface area, and hence high lifting capacity. This leads to foaming in a significant part of the slime on the surface of the water catchment spouts, poor water settling in the slime compactor, and consequently, increased extent of continuous blowing and lower «cut-off» water quality. «Cold» coagulation has a positive effect on the hydraulic mode of clarifiers, and specifically helps to suppress floating slime by the action of released gases.

Water treatment at lower temperatures is also possible in ultrafiltration systems. Research shows [10] that although the coagulation process in cold water (at temperatures of 8–11 °С) is worse than in heated water, treatment by the ultrafiltration method remains stable with only a small increase in coagulant dosage. Water treatment at lower temperatures increases water viscosity, resulting in better membrane retaining ability, which gives the ultrafiltration method an advantage over traditional pretreatment methods, where lower water temperature leads to larger doses of reagents and aluminium slip into clarified water. Lower clarified water temperatures have a favourable impact on the work of reverse osmosis membranes.

3. Conclusion

High energy and resource efficiency indicators at thermal power plants may thus be achieved by various technological measures, including equipment modernization, improved efficiency of power generation units, and others. In addition to this, there is a need for modernization of auxiliary
equipment, particularly water treatment systems. Furthermore, high energy and resource efficiency indicators may be achieved both at currently operating and new water treatment systems at thermal power plants.

References

[1] Tumanovskii A.G., Shvarts A.L., Somova E.V., Verbovetskii E.K., Avrutskii G.D., Ermakova S.V., Kalugin R.N., Lazarev M.V. Review of the coal-fired, over-supercritical and ultrasupercritical steam power plants // Thermal Engineering. 2017. Vol. 64. № 2. pp. 83–96.

[2] Tumanovskii A.G., Shvarts A.L., Verbovetskii E.Kh., Tugolukov E.A., Smyshlyaev A.A., Nesiolovskii O.V., Petrova N.V. A coal-fired boiler for a new-generation power unit for ultrasupercritical steam conditions // Thermal Engineering. 2009. Vol. 56. № 6. pp. 447-455.

[3] Supranov V.M., Ryabov G.A., Mel'Nikov D.A. Studying the possibility and advisability of using a Pp-1000-25-585 circulating fluidized-bed boiler in the oxyfuel combustion mode // Thermal Engineering. 2011. Vol. 58. № 7. pp. 593-601.

[4] Dub A.V., Skorobogatykh V.N., Shchenkova I.A. New heat-resistant chromium steels for a promising objects of power engineering // Thermal Engineering. 2008. Vol. 55. № 7. pp. 594-601.

[5] Yurchevskii E.B., Larin B.M. Development, study, and introduction of water-treatment equipment with improved environmental characteristics // Thermal Engineering. 2005. Vol. 52. № 7. pp. 532-538.

[6] Larin B.M., Bushuev E.N., Larin A.B., Karpychev E.A., Zhadan A.V. Improvement of water treatment at thermal power plants // Thermal Engineering. 2015. Vol. 62. № 4. pp. 286-292.

[7] Panteleev A.A., Riabchikov B.E., Khoruzhii O.V., Gromov S.L., Sidorov A.R. Membrane technologies in the industrial water treatment –Moscow: DeLi plus, 2012. 429 p.

[8] Bushuev E.N., Eremina N.A., Zhadan A.V. Analysis of Water Treatment Modern Technology at Heat Power Plants // Vestnik of Ivanovo State Power Engineering University. 2013. №1. pp. 8-14.

[9] Yurchevskii E.B., Solodiannikova Yu. V., Pichugina M.A., Kavun O. Yu. Vortex reactors in the schemes of utilization of concentrate of reverse osmosis units at Thermal power plant and Nuclear power plant // Tyazheloe mashinostroenie. 2016. № 6. pp. 9-14.

[10] Zhadan A.V., Bushuev E.N. Rationale for selecting water treatment schemes at thermal power plants based on ultrafiltration technique // Vestnik of Ivanovo State Power Engineering University. 2014. №2. pp. 5-9.