Mathematical calculation of additional cooling methods to achieve the established temperature regime at the reservoir-cooler of Zainskaya state district power plant

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Abstract. A natural and technical complex, including the industrial part - the turbine condenser and cooling system, and the natural part - the cooling reservoir with the surrounding atmosphere, is one of the options for the operation of the circulating system technical water supply of thermal power station and nuclear power station. For cooling equipment Zainskaya state district power plant as a pond-cooler is used Zainskoe reservoir. According to the available data on the reservoir-cooler of Zainskaya state district power plant, the average water temperature in comparison with the natural temperature of the water body in summer months exceeds the current requirements, which negatively affects the functioning of the reservoir and the operation of the power plant itself. The mathematical analysis of the reservoir cooling capacity and the technical justification for the introduction of additional methods for achieving the optimum temperature regime at the point of heat exchange water discharge of the Zainskaya state district power plant are carried out in the article. According to the obtained results, the expected water temperature in the hottest month of the year as a result of wastewater discharge will not exceed a critical temperature maximum of 28 °C.

The Zainskoe reservoir was created on the Stepnoi Zai River in 1965 as a cooling reservoir at Zainskaya state district power plant. Zainskaya state district power plant with a capacity of 2,200 MW is located on the left bank of the reservoir. Technical water supply of the state district power station is carried out according to the circulating scheme with the circulating water cooling in the reservoir. Heated water comes through two outflow channels. There is also a winter outlet channel from which the warmed waters are discharged into the middle part of the reservoir. The water intake for supply to the station is carried out from its middle part by three shore pumping stations, which allows the most intensive using the reservoir water area for heated water circulation.

Zainskoye reservoir performs the following functions of a diversified body of water [1]: reservoir-cooler state district power plant, recreational zone of Zainsk and Zainsky municipal district, fishery. The reservoir is not used for drinking water supply in adjacent settlements.

During the existence of the reservoir, a considerable amount of secondary deposits accumulated, which led to a reduction in its volume, the formation of extensive shallow-water areas, and active overgrowth by higher aquatic vegetation, which in turn leads to a decrease in heat exchange and intense thermal contamination of the reservoir [2].

The temperature regime formation of the reservoir is conditioned by weather conditions and the introduction of the heat in the reservoir with the circulating cooling water heated at the state district power plant. In the summer, the reservoir experiences the greatest heat load due to high outdoor conditions.
temperatures and the maximum number of plant equipment operating, determined by the complex summer operating conditions of the Russian energy system. Recent years studies found that during the summer period it is not possible to achieve the necessary cooling effect of the circulating water, on which the actual power of the power plant depends [3,4]. There several reasons can be, for example, the reduction of evaporative cooling from the water surface [5]. The degree of influence of the state district power plant activity on the reservoir, including water temperature changes in it, has not previously been evaluated.

The hydrological characteristics of the reservoir, when sewage enters in it after being used for cooling needs of the Zainskaya state district power plant equipment, must satisfy the following requirements:

- the water temperature should not increase in comparison with the natural temperature of the water body by more than 5 °C, with a total temperature increase of no more than 28 °C in summer and 8 °C in winter,
- the dissolved oxygen concentration in the water should be at least 4-6 mg/dm³ [6-8].

According to Zainskaya state district power plant temperature measurements at the reservoir-cooler of Zainskaya state district power plant, the average water temperature in comparison with the natural temperature of the water body exceeds the current requirements in the summer months, which negatively affects the reservoir functioning and the operation of the power plant itself. According to the actual measurements, the maximum water temperature in the reservoir during the operation of state district power plant in the summer months can reach 35 °C.

**Mathematical analysis of the reservoir-cooler efficiency at Zainskaya state district power plant**

The reservoir-cooler calculation was carried out on the basis of [9]. Methodical instructions apply to fully loaded cooling ponds (specific heat load above 150 W/m²), specially designed for cooling circulating water in the circulating water supply systems of TPS.

To evaluate the efficiency of the circulating water cooling, it is recommended to use the temperature distribution parameter \( P_T \) and the utilization factor \( K_{ev} \):

\[
K_{ev} = \frac{\text{Fact}}{F}
\]

The total area of the reservoir-cooler \( F \) for today is 15.36 km². According to the initial project, the reservoir area was 20.45 km². The active cooling area in summer is \( F_{act} \) 8.7 km² [10]. Then \( K_{ev} = 0.566 \).

The parameter \( P_T \) reflects the temperature decrease of the cooled circulating water relative to the average temperature level in the cooling pond and is determined by the formula:

\[
P_T = \frac{T_s - T_{int}}{\Delta T}
\]

where \( T_s \) is the mean free surface (mid-surface) temperature of the reservoir-cooler, °C; \( T_{int} \) - water temperature at the water intake of TPP, °C; \( \Delta T = \Delta t_c \) - water temperature at the input and output from the capacitors (for July 2016 \( \Delta t_c = 7.8 \) °C). The average surface temperature \( T_s \) shall be taken as the average over the reservoir at the sampling points on 07/07/2016 from the temperature measurement schedule in the Zain reservoir. The average temperature at the water intake \( T_{int} \) will be taken as average at the shore pumping stations for the same day. If \( T_s = 25.4 \) °C, \( T_{int} = 23.9 \) °C, then \( P_T = 0.19 \).

According to the obtained values of the efficiency indicators for cooling reservoirs, we determine [9] that the Zainskoye reservoir refers to an elongated narrow type with a longitudinal direction of flow in one part and a stagnant zone in another. The water outlet and water intake are located so that the circulation zone occupies only a part of the reservoir area.
Next, we find the thermal load on the cooling pond. The technical water supply flow for the turbine K-200-130, operating at Zainskaya state district power plant, is 25,000 m$^3$/h [11]. There are 11 turbines in operation at the moment. Hence the estimated water flow maximum is:

$$V_m = 25000 \text{ m}^3/\text{h} \cdot 11 = 275\,000 \text{ m}^3/\text{h} = 6.6 \cdot 10^6 \text{ m}^3/\text{day}$$

(3)

The maximum monthly average water temperature to the capacitors inlet for August is $t_{c1} = 29.6 \degree C$, at the outlet $t_{c2} = 37.6 \degree C$ (average for August 2016). Heating water in turbines condensers is taken according to actual data:

$$\Delta t_c = 37.6 - 29.6 = 8.0 \degree C$$

(4)

The mass water flow taking into account the water density at these temperatures is:

$$G = \Delta V_m \cdot \rho = 275\,000 \text{ m}^3/\text{h} \cdot 994.26 \text{ kg/m}^3 = 273420 \text{ ton/h}$$

(5)

The heat amount supplied by the station's technical water in the water tank-cooler $\Delta Q$ is:

$$\Delta Q = G \cdot \Delta t_c = 273\,420 \text{ ton/h} \cdot 8.0 \degree C = 607\,600 \text{ kcal/s} = 2\,545\,844 \text{ kJ/s} = 2546\,MW$$

(6)

The difference in the outlet and inlet water temperature in the reservoir changes on average by 2.34 °C (according to temperature measurements). If we take into account that the water flow in the river (flow effect) in July is equal to 6.38 m$^3$/s (according to state district power plant), due to the influence from the Stepnaya Zai river flow, 62.6 MW/s of heat is taken from the reservoir. In this period, the forecast load (according to the retrospective analysis of actual regimes) was 15% of the estimated maximum station load:

$$15\% \cdot \Delta Q = 0.15 \cdot 2546\,MW = 381.9\,MW$$

(7)

The natural heat loss from the Stepnaya Zai River running water of (62.6 MW/s) is 16.4% of the predicted thermal discharge of the station, i.e. the efficiency of the reservoir-cooler at this time was:

$$\eta_{ef} = 100\% - 16.4\% = 83.6\%$$

(8)

Since the total area of the reservoir is $F = 15.4\,\text{km}^2$, then the specific heat load without insolation is:

$$Q_{esl} = \Delta Q/ F = 165.3\,W/\text{m}^2$$

(9)

$Q_{esl}$ is more than 150 W/m$^2$ and the application of [9] is legitimate.

Let's perform an approximate evaluation of the cooled circulating water temperature. Using the nomogram of the reservoir-cooler calculating [9], we will find the temperature increasing in the cooling pond when the state district power plant works. We get that at a certain equilibrium temperature, $T_{eq}$ (18.8 °C for August), wind speed $W$ (2.5 m/s) and temperature difference in turbine condensers $\Delta T$ (8.0 °C), the maximum overheating at the water intake $\delta T_{max}$ in relation to the temperature $T_{eq}$ is 7.4 °C.

So, under maximum load, state district power plant can ensure the water temperature in the reservoir is not higher than 28 °C in the summer months only if the water temperature at the entrance to the reservoir is not more than 20.6 °C. If the water temperature is 28 °C, the station will have to reduce the load to 0 with the termination of the thermal discharge completely.

In order to increase the load on state district power plant under these conditions, it is necessary to use complex technical measures for additional cooling, for example, air cooling or others.
Technical measures to achieve the established temperature regime at the reservoir-cooler of Zainskaya state district power plant

For air cooling, it is proposed to use the areas of supply and discharge channels, and on the ground along their banks to place spray devices.

It is necessary to calculate under what weather conditions the water temperature in the discharge channels can be reduced to 28 °C spray devices using. The average monthly relative humidity of air at 3 p.m. of the warmest month is 55%. We take the same values for the Zainsky reservoir. In ideal conditions, the cooling zone width should be taken as equal to the heating of the water in the condenser, i.e. \( \Delta t = 8 \) °C.

However, we can choose the cooling zone width of spray units only 4 °C, as the minimum possible, based on the following limitations:

1. it is economically unprofitable to cool down by less than 4 °C;
2. It is possible to cool more with the help of spray devices, but at a low ambient temperature, since the cooling capacity of the spray devices depends on the climatic conditions (air temperature and humidity).

Thus, for a given cooling zone width at 4 °C, to cool the water to the required water temperature at a discharge of 28 °C at a fixed humidity of 55%, the outside air temperature should not be above 27.5 °C (according to the nomogram for the temperature calculating of the chilled water in the spray unit and the psychrometric table) [12]. Taking into account the wind corrections, the shape of the spray pool, the water pressure before the nozzles, we get that the outside air temperature at 55% humidity should not be above 30 °C.

Average for 2015 - 2017 years in Zainsk, the duration of periods with temperatures above 30 °C is 72 hours per year. In this period, the spray devices operation will be inefficient, because they will not be able to cool the water by 4 °C and, consequently, the required water temperature at the discharge of 28 °C will not be reached.

Also, the spatter devices operation is impractical at water temperatures at the inlet of steam turbine condensers below 20 °C, when even with a maximum station load due to water heating at 8 °C, the temperature at the discharge will always be below 28 °C. The frequency of such modes is 6544 hours per year. The rest of the time - 2216 hours a year, spray devices are in demand to reduce the water temperature at the discharge in the reservoir below 28 °C.

Thus, the estimated time of spray devices using will be the difference in the duration of their demand period for the initial water temperature (2216 h/year) and the period of their inefficiency due to too high outside air temperatures (72 h/year) - 2,144 hours per year.

To cover the remaining small period of excessively high outside air temperatures (72 h/year), it is proposed to supplement the spray devices operation with the installation of a permanently operating ejection device in the discharge channel. According to our calculations, such an ejector will reduce the water temperature in the channel by approximately 1 °C. Since this is not enough, it is proposed to install 10 submerged axial pumps parallel to the ejector with a capacity of 20,000 m³/h.

The estimated operating time of the mixing pumps work will be 3 days per year (72 hours), and the ejector should function continuously. The pumps installation will allow, together with the ejector, to reduce the water temperature in the discharge channel by 3 °C.

Conclusions and recommendations

1. At present, the Zainskoye cooling reservoir does not meet the requirements for the temperature regime, which provides a general increase in temperature to no more than 28 °C in summer and 8 °C in winter in comparison with the natural temperature of the water body;
2. To achieve a temperature regime in the summer months in accordance in the reservoir-cooler and ensure the full station operation with the required capacity, it is proposed to implement the following technical measures:
   - To install spray units on the banks of the supply and discharge channels. The estimated time of sprays using will be 2144 hours per year. In the period of the highest outdoor temperatures (72 h/year),
spray units can not independently provide sufficient the discharged water cooling, but they can be used in combination with additional cooling methods (dilution, ejection, etc.). Spray devices also saturate the water with oxygen, which allows a radical solution to the problem with oxygen deficiency in waste water.

- To install a simplified ejection device of the proposed design and 10 mixing pumps in the discharge channel. The estimated operating time of the mixing pumps will be 3 days per year (72 hours), and the ejector should function continuously.

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