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HYDROTHERMAL MODE OF THE FLOW-THROUGH RESERVOIR-COOLER WITH RESPECT TO ITS MORPHOMETRIC CHANGES

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Наведені дані про морфометричні зміни за період експлуатації протічної водойми-охолодника теплової електростанції. Подано гідротермічний аналіз температурного режиму даної водойми з двома випусками в неї нагрітої циркуляційної води. Розглянута кінетика потоків в акваторії біля водоскиду в нижній б'єф з врахуванням допустимих температур води. Дана оцінка впливу замулення водойми на стан охолодника циркуляційної води

Ключові слова: протічна водойма-охолодник, замулення водойми, температура води в пригреблевій акваторії

Приведены данные о морфометрических изменениях за период эксплуатации проточного водоема-охладителя тепловой электростанции. Дан гидротермический анализ температурного режима данного водоема с двумя выпусками в нее нагретой циркуляционной воды. Рассмотрена кинетика потоков в акватории у водосброса в нижний бьеф с учетом допустимых температур воды. Дана оценка влияния заиления водоема на состояние охлаждающей циркуляционной воды

Ключевые слова: проточный водоем-охладитель, заиление водоема, температура воды в приплотинной акватории

1. Introduction

Discharge of circulating water of a thermal power plant (TPP) for cooling occurs far from water intake of a system of technical water supply (TWS) in water reservoirs-coolers (RC) of shallow and medium depths. As a result, an active area increases and temperature of cooled water decreases. This refers to the filled RC and the flow-through RC fed by small rivers A reservoir-cooler is a regulator of a surface flow. It provides reversible water supply. In deep RC (with a depth exceeding 6.0 m), especially with deep water intakes, we can find the latter near a place of disposal (discharge) of circulating water into RS. In the circulating water supply system of the Dobrotvir thermal power plant, the discharge of heated circulating water to RC occurs both to the tail part of it and to the head of *the reservoir-cooler* near the water discharge facility. The basic factor, which characterizes a water temperature during a discharge of circulating water is a natural temperature mode of the reservoir-cooler. Taking into account that disposal of warm water of TPP occurs to the head part of a running water reservoir-cooler also, a temperature mode in a water catchment area has a water preservation importance. An average water temperature in a reservoir and water temperature in a river, which flows into the lower water, depends on it.

The relevance of present study is in determining the effect of silting of a flow-through reservoir during an operation period on its characteristics as a cooler of circulating water of TPP, that is, an active area and a temperature mode. After all, a change in the volume and active area of RC affects the temperature of cooled circulating water, and thus the vacuum in a condenser of TPP turbines and the power of an energy generating unit.

2. Literature review and problem statement

As a rule, the purpose of calculation of reservoirs-coolers (RC) of technical water supply systems for TPPs and NPPs is determining the average temperature of cooled water in a water area and the required area of RC. We can forecast a hydrothermal mode of a reverse water supply system at the design stage, as well as in the course of special thermal research, based on the equation of a thermal balance [1].

In this case, the thermal balance of the hydrothermal state of a reservoir-cooler for an unstable thermal mode takes into consideration:

– a flow of heat to RC with circulation water and water from other sources, which is discharged into RC, as well as absorption of heat of solar radiation;

– heat transfer, radiation, and residual heat in a reservoir and a circulation stream entering the water intake of TWS.

The general equation of the thermal balance for RC takes the form:

$$S_1-S_2+S_3-[\alpha_e(e_m-e)+\alpha_k(t-\theta)-R+\Delta I]\Omega= \\ =W\cdot c\cdot\rho(dt/dT), \quad (1)$$

where S_1, S_2 is the heat capacity of the recycled water, which is discharged and taken from RC; S_3 is the heat capacity of the source of water feed discharged into RC; $\alpha_e(e_m-e)$ is the heat consumption for evaporation; $\alpha_k(t-\theta)$ is the heat consumption for convective heat exchange between water and air; e is the absolute humidity of the air; e_m is the maximum elasticity of water vapor; R is the radiation balance for RC water area in the estimated decade; Θ is the average air temperature; α_e is a coefficient of heat transfer by evaporation; α_k is a coefficient of heat transfer by convection; T is the average water temperature of RC; t is the duration of research (or a calculation period); W is the volume of an active zone of RC; Ω is the area of active water of RC; ΔI is the additional effective radiation of a water surface due to the heating of a cooler by water discharged from TPP.

A disadvantage in determining the magnitude of an active area of RC based on the equation of thermal balance [1] is that diffusion of a transit flow through a water area of RC is rather approximate. There are no recommendations for determining the depth, width, and area of the active volume W in $W\cdot c\cdot\rho(dt/dT)$ component of the thermal equation. Thus, to obtain the equation with one unknown value, we take approximately that $W=\Omega H$, where H is the approximate average depth of RC. Since over the observation period of $T\approx 10$ days a change in average water temperature dt for each season is different, then we obtain different values of an active area of RC, which is not logical.

A warm summer period with high temperatures of air and water is defining for hydrothermal calculations of RC of TWS of power plants with running water. As a rule, the speed of wind is low during this period, which does not contribute to the cooling of circulating water in RC. Water cooling occurs in RS mainly due to evaporation in this period. Special research organizations determine the effectiveness of using RC during an operation period according to special methods. They determine the size of an active area Ω. The main indicator of RC's operation is the temperature of the cooled circulating water at a place of its intake by a circulation pump station.

Water temperature changes in the water area of slow cooling in the functional dependence on $t_2=f(S_c, S_e, R, V, \lambda)$, that is, the magnitude of insolation (R), heat transfer (S_e) from a water surface into the air by evaporation; heat transfer through a water surface into the air by convection (S_c); a water speed – V; a coefficient of heat transfer (λ). At the same time, a coefficient of heat transfer by evaporation of a nearby RC zone α_e=0.80–0.50 Mcal/(м^2 day mm), at the end of flow-through RC is 50–80 times lower [2]. A calculation of the heat balance method does not explain these factors. Dependence [2] describes an experimental value of the intensity of cooling of a transit water flow (for a period of summer high air temperatures) [2]:

$$\Delta t=a(1-e^{-bT}), \quad (2)$$

where T is the duration of water flow in RC; a, b are coefficients (a=8.72175; b=0.32245) obtained during processing of observation data on the temperature mode of RC using a method of mathematical statistics. The above experimental dependence with [2] does not make it possible to determine water temperature in RC below a surface transit flow.

Paper [3] reports results of research, which determined that one observes temperature stratification from 2.0 °C in water areas with a depth of 2.5–3.0 m. However, there is no theoretical substantiation of such hydrothermal processes in the work. Previous papers of these authors include data on the degree of using many RC of TPP, in particular that the active area of RC is sufficient from 4.0 to 6.0 m^2 per 1 kW of installed capacity.

The influence of thermal emissions on individual reservoirs, lakes or areas of rivers may manifest itself differently depending on: biological, hydrological, and physical-chemical state of a reservoir; changes in air temperature. The average temperature of water in natural reservoirs of Ukraine (in the hottest decade of the year) should not be higher than 28 °C due to the technogenic heat load. In this case, an acceptable increase in the natural water temperature is not higher than 3 °C. In most countries, a technogenic increase in water temperature from the natural level is also limited to 3.0 °C, but in industrial regions this indicator reaches 5.0 °C [4, 5]. However, these comparisons are given for autumn and spring seasons and there are no conclusions about a negative impact of a heat load on flora and fauna over the mentioned seasons.

It is advisable to investigate an increase of water temperature in spatial models for the integrated control of a water body and an influence on the integrity of aquatic organisms. We can believe that there is sufficient legal and regulatory framework to control physical-chemical contamination of water bodies in Ukraine. The problem is in the presence of the appropriate technical base for monitoring and proper timing.

A numerical method for modeling thermal processes in RC of TPP by a three-stage solution to the three-dimensional Navier-Stokes equations and the temperature equation for a liquid flow is a significant contribution to the theory of thermal calculations [6]. However, its use in practice is complicated, and there is no verification of the higher accuracy of this method in relation to existing ones.

A use of groundwater instead of river water for systems of technical water supply of TPP and NPP eliminates a negative effect of elevated water temperatures [7]. However, reconstruction of the existing TPP is labor-consuming and it requires appropriate hydro-geological conditions, although it is useful for the preservation of rivers.

Construction of solar power plants instead of coal power units (with a ban for using for direct-flow water supply systems of TPP in some US states) eliminates the problem of thermal pollution of reservoirs [8]. However, such solutions are not possible for all countries of the world.

Air cooling for TPP turbine condensers can eliminate technogenic influences on a state of rivers [9]. However, it is difficult technically and it is expensive to rebuild the existing TPP.

A work [10] presents the results of hydrothermal studies of the Surgut TPP-2 RC (Russia). It recommends constructing a flow distribution unit to increase cooling of water in the mentioned RC. Such technical solutions are inappropriate for narrow flow-through RC.

The increase in the natural temperature of water in reservoirs-coolers of circulating water of TPP is 3...5 °C. Paper [11] presents a global integrated model for estimation of ways of transformation of a power system with a limitation of temperature influence of 2 °C on fresh water. The proposed measures for reduction of the use of fresh water [11] are acceptable for thermal and nuclear power plants in coastal regions only. In addition, a use of air cooling for TPP (instead of river water) leads to a reduction in their power and efficiency. The authors did not take into consideration the following:

– water temperature changes with depth;

– there is a seasonal variation of a water temperature;

– there is a possibility of reduction of a thermal load on a water area of RC by variants of circulating water discharges.

We identified the following outstanding issues after the analysis of the above-mentioned literary sources:

– issues related to an influence of silting of a reservoir-cooler during the operation period on a temperature mode of a use of RC water area;

– use of two discharges of heated circulating water to RC.

3. The aim and objectives of the study

The purpose of the study is to investigate a degree of silting of a flow-through reservoir-cooler of TPP over operation period and an influence of morphometric changes in RC on its temperature and temperature of circulating water.

To achieve the set aim, the following tasks have been solved:

– assessment of a degree of change in morphometric characteristics (W, H) of a flow-through reservoir-cooler as a result of its silting over a 50-year period of operation and an influence on the active area of RC;

– assessment of an influence of RC silting on a degree of cooling of circulating water and on an average RC temperature in general;

– determination of an influence of discharge of a part of circulating water of TPP to the head on a temperature of river water flowing from a reservoir;

– development of recommendations for prevention of exceeding the maximum acceptable water temperatures in a river below a RC dam.

4. Materials and methods to study the morphometric changes and temperature mode of RS

The object of the study is a flow-through reservoir-cooler of the system of technical water supply (TWS) of a power plant with the installed capacity of 510 MW. The discharge of heated circulating water of TPP to RC occurs by two channels; one in the tail section, the other in the head section of a reservoir-cooler (Fig. 1).

We carried out temperature study of the reservoir-cooler according to the standard method [1]. We measured water temperature in RC on the surface through a depth of 1.0 m and at the bottom at definite widths of the reservoir. We used thermometers and laboratory mercury thermometers with sections of 0.1 °C for temperature measurements.

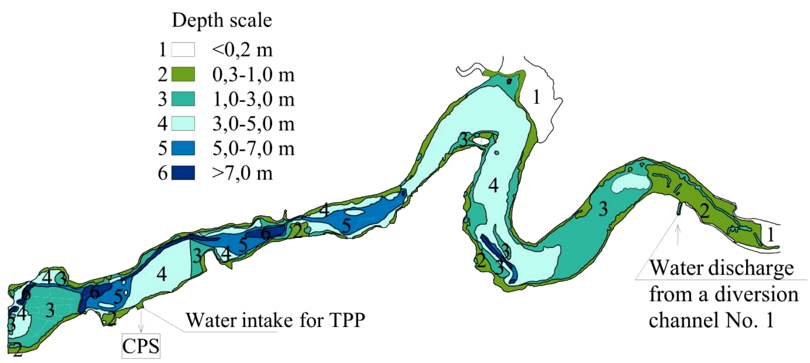

Fig. 1. Map of depths of the Dobrotvir reservoir in the water area from the water discharge to the water intake of TPP

We measured depths of water in RC from a motor boat with echo sounders with coordinate dimensioning by the water area using the GPS navigation device. At the same time this tool measured a depth of silt. In shallow water, we determined thickness and mechanical composition of silt further determined by means of geological drilling. We defined a volume of silting of RC as the difference between an actual volume of water for the period of the study and a volume at the beginning of operation.

5. Results of the study of a flow-through reservoir-cooler

5. 1. Morphometric studies of a reservoir

According to the measurements, a volume of silting of the reservoir is 0.88 million m^3, while the total volume of RC is 14.2 million m^3. Table 1 gives other morphometric characteristics of the Dobrotvir reservoir after 50 years of its use.

Table 1

Morphometric characteristics of the Dobrotvir reservoir after 50 years of use

Characteristics	Project value	Actual value
RC area at NSL, km^2	6.96	5.3984
Total volume at NSL, million m^3	14.8	14.2
Area of the active zone of RC, km^2	5.00	4.65 in summer 3.25 in winter
Maximum depth, m	4.00	7.00
Average depth, m	2.13	2.63
Area of shallow water with a depth of up to 2 m at NSL, m^2	3.00	3.85
Average depth of the active zone, m	2.70	*

*Note: * – we did not determine the characteristic*

The area of a shallow water is already 55 % of the entire water area. Shallow water zones with depths up to 2 m increased by 28 %, however, we can consider a water depth of up to 1.5 m as shallow water for this RC.

As a result of field measurements (Fig. 1) we established that the area of RC decreased by 1.56 km^2 due to silting and overgrowth of the coastal water area. Outside of the coastal area, there is no silting of RC and there is a process of transportation of silt through the flow of water to the river to the lower water. The depth of shallow water up to 2 m (an average of 1.0 m) is only 22 % of the actual volume of RC. The total volume of RC decreased not so much – only by 9.6 %. Therefore, the average depth of RC increased by 0.5 m with a significant decrease in the shallow part of RC.

The determination of a depth of the active RC zone by the thermal balance method is approximate at some degree, since the value is calculational in the method and depends on the exact value of Ω characteristic. However, in the case of an increase in the average RC depth, we can accept an increase in the depths of the active zone proportionally.

We should determine the actual value of RC Ω based on compatible temperature and hydraulic studies of RC flowage. Fig. 2 shows one of the characteristic results of thermal study of RC under the following conditions: t_1=28.5 °C; t_2=28.8 °C; Q_1=6.2 m^3/s; Q_2=13.0 m^3/s; Q_4=19.2 m^3/s; air temperature θ=21.5 °C; natural water temperature t_n=19.2 °C.

5. 2. Analysis of hydrothermal processes of flow-through RC and a use of temperature stratification of water

A temperature of cooled water depends on a number of factors: a specific hydraulic load on the active RC area, temperature of water and air, wind speed, etc. The water temperature in the water area of the reservoir, that is, along the length of a transit flow, is significantly different. The transit flow of circulating water from its place of discharge to a water intake by a circulation pump station usually has a zone of fast active cooling and a zone of slow cooling.

About 75 % of the total flow of circulating water goes through number 2 diversion channel. RC water area, to which warm water goes through mentioned channel, is shallow water. However, in the near zone (from the water discharge), the most intense cooling of circulating water occurs at 3–4 °C (≈50 % Δt). In addition, it helps to mix colder river water.

In the water catchment area of RC, a surface water temperature is higher by 2.0 °C than in the central part of the reservoir. This is a consequence of:

– a short distance from a place of discharge of circulating water through the channel number 1, and hence a lack of time to cool it;

– a greater hydraulic load and a smaller active RC area for the given volume of circulating water.

If we analyze water cooling at the depth of a transit flow in RS, then the most intense cooling occurs in a surface layer up to 2.0 m deep. Below, at a considerable length of water flow, the temperature of water is in the equilibrium at a certain depth, but it is much higher than the natural temperature. We discovered from field study that the clearest boundary of temperature stratification of the flow (Δt= =2.0...3.0 °C) for shallow and middle depths of RC passes at a depth of 1.5 ... 2.0 m or lower than a surface of water.

By the length of running of the transit flow to RC, the largest portion of cooling of circulating water is at the beginning of discharge into the reservoir. Although a specific thermal load on RC in this zone is much higher than in the middle or the end of the reservoir. Duration of intensive daily cooling of water in RC is 18–20 hours.

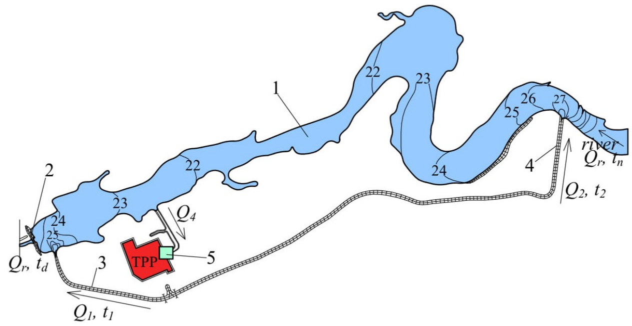

Fig. 2. Plan of the reservoir-cooler in isotherms for experimental conditions: 1 — reservoir; 2 — dam; 3 — discharge channel No. 1; 4 — discharge channel No. 2; 5 — circulation PS; t_1, t_2 — water temperatures in discharge channels No. 1, No. 2, respectively, t_n — natural water temperature (isotherms are in °C); Q_1, Q_2 — flow of circulating water discharged to RC through channels No. 1 and No. 2, respectively; Q_r — water flow-through in the river

The water catchment area, where the depth is 5.0–6.0 m and deeper, is clearly stratified. We can determine water temperature of the upper active water flow in RC (for a determinative hot summer period) according to the dependence using formula (2):

$$t_{3a}=t_1-a(1-e^{-bT}), \quad (3)$$

where t_1 is the temperature of circulating warm water discharged of TPP through channel No. 1.

The average temperature of the bottom layer t_{3b} (Fig. 3) of water is lower than the surface by 3.0 °C approximately.

$$t_{3b}=t_{3a}-3.0\ ^{\circ}\mathrm{C}. \quad (4)$$

Consequently, according to formula (4), it is possible to predict the temperature of water discharged from a flow-through reservoir into the river as sanitary outflows in summer. This is important for the summer period.

Heat transfer to the end section of the flow-through reservoir is substantial for a shallow surface layer in windy weather only due to wave, drift and dynamic mixing of water and turbulent and convective heat conduction. Almost all cooling occurs due to evaporation in the summer warm period. In the hot summer period of a year (in daylight time) in the final stage, a transit flow in RC is not cooled but additionally heated. In addition, we should keep in mind that average daily water temperatures can vary by 0.3–5.0 °C for the regions of Ukraine. Daily changes in the natural temperature of water depend on changes in air temperature, solar heat, meteorological factors. In particular, an increase in average daily air temperatures by 0.4 °C (or a decrease by 0.6 °C) leads to an increase in water temperature by 0.1 °C (or a decrease of 0.1 °C).

About 4.5 km^2 of water is sufficient for operation of RC of TPP and NP of 1000 MW capacity. Therefore, for the given flow-through RC, which serves TPP N=500 MW, the existing area of RC is sufficient. Of course, silting of RC, which occurred during a long period of operation, affects its temperature map, but primarily the water temperature in shallow waters, where the depth is less than 0.5–0.7 m.

There is, in fact, no temperature stratification of water, and its flow is small, or absent. In addition, a predominant amount of silting took place, as a rule, in the initial water area of RC and in the narrow coastal part of it. The latter does not apply to the active area of RC.

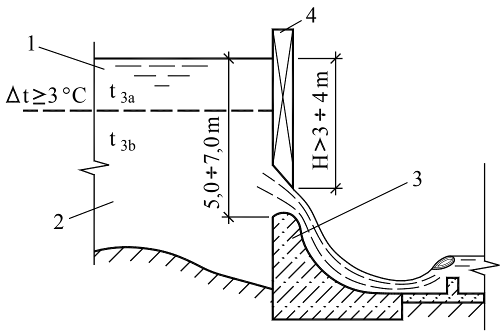

Fig. 3. Use of temperature stratification of RC for water discharge to the lower water (river) from RC: 1 – the upper layer of water of the flow-through reservoir-cooler; 2 – the deep layer of the flow-through reservoir-cooler; 3 – discharge facility; 4 – controller of the lock gate; t_{3a}, t_{3b} – water temperature at the depth of the stratified reservoir

5. 3. Kinetics of the flow of water in the head part of RC and regulation of water discharged into the river

The kinetics of a flow of circulating water at the exit from the discharge channel of RC changes, which affects the speed diagram (Fig. 4) and the area of the living cross section of the flow. Water with elevated temperature enters the water catchment area and the river under the influence of the operation of the discharge facility.

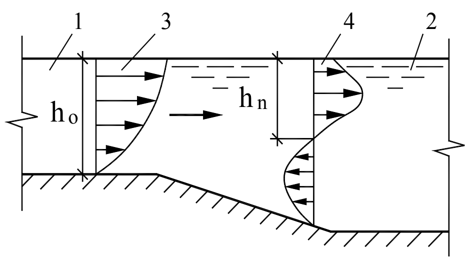

Fig. 4. Diagrams of water speed at its discharge from the discharge channel in RC: 1 – longitudinal section of the discharge channel; 2 – flow-through reservoir-cooler; 3 – diagram of speeds of uniform flow of water in the channel; 4 – the same of uneven flows in RC; h_0 – depth of water of uniform, flow; h_n – depth of the flow of uneven flow in RC

This may lead to violations of environmental norms for exceeding the acceptable temperature of river water in summer. This is especially true for surface water discharges. If a structure of a discharge facility has the appropriate equipment, then it is possible to discharge deeper colder water into the lower water (into the river) (Fig. 5).

That is, volumes of water from the depth of more than 2.0 m will get first and foremost from a stratified reservoir-cooler to a discharge facility in the water catchment area. Therefore, if discharge of deep layers of water provides flowage of RC in the summer period then sanitary norms regarding thermal pollution (rivers below RC) are provided.

The main purpose of the discharge channel No. 1 is to prevent possible ice complications in operation of the discharge facility. In addition, a discharge of heated water through the channel No. 1 increases the active zone of the reservoir. However, its use in the summer may lead to violations of environmental regulations. Due to reasons of objective and subjective nature, water in the head of RC flows throughout a year, that is, in the summer.

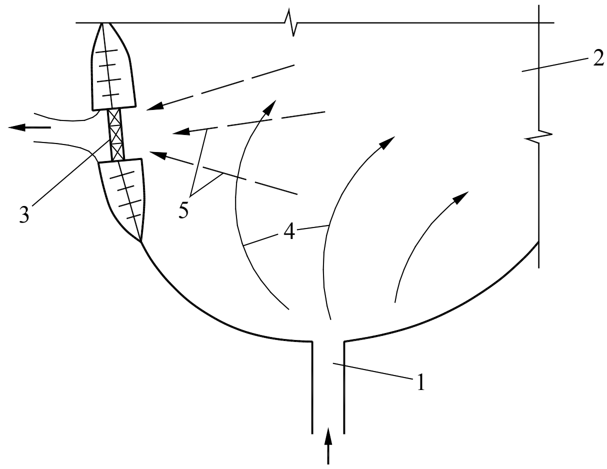

Fig. 5. Direction of flows of circulating water in the water area of its discharge into the head of the flow-through reservoir-cooler: 1 – discharge channel of circulating water to the water catchment area; 2 – flow-through reservoir-cooler; 3 – discharge system with controller of lock gate; 4 – direction of the surface flow; 5 – direction of the deep flow to the discharge

Under conditions of running water, a surface-active water flow from the water catchment area may be directed to the water intake of CPS (Fig. 5) if the supply of water Q_1 through the channel No. 1 exceeds a sanitary discharge from the reservoir ie flow-through Q_r. An additional condition for the ratio of redistribution of costs Q_1 and Q_2 through the discharge channels No. 1, 2 (Fig. 2) can be keeping the same specific hydraulic loading in upper and lower water areas of RC, that is,

$$Q_1/\Omega_1=Q_2/\Omega_2, \qquad (5)$$

where Ω_1, Ω_2 are the active areas of a water area of RC, affected by flows of water from discharge channels No. 1 and No. 2, respectively.

In general, a discharge of circulating water for cooling through two channels – in the upper and in the water catchment area of flow-through RC increases its active area. As a result, a temperature of cooled water for TPP and an average temperature of RC decreases.

A similar scheme of close location of places for discharge of warm water from a deep water intake of a circulation pump station is in thermal and nuclear power plants. In this case, it ensures selection of considerably colder water for technical needs. This confirms possibility of discharge of heated circulating water to the head of flow-through RC, where a discharge to a river is close.

6. Discussion of results of studying the hydrothermal mode of a flow-through reservoir-cooler with respect to morphometric changes

The object of performed hydrothermal study relates to coolers of systems of technical water supply for thermal and nuclear power plants. The feature of such cooler is that it is a flow-through reservoir and two outflows of circulating water.

We obtained the following results in the study of flow-through RC:

– on a degree of RC silting for 50 years of operation, reduction of the area of the water area and its volume;

– temperature map of RC and degree of cooling of circulating water;

– water temperature in a catchment area, that is, in the place where it is discharged into a river;

– kinetics of a water flow in a catchment area is important to control the temperature of water discharged into lower water.

Silting of the flow-through RC occurred due to the arrival of mineral and organic impurities with river water. Sand from a coastal area with surface waters, as well as silting organic plants come to the water area of RC also. Sediment of river silt naturally occurred at the tail part of RC. The central and tail parts of RC were not silted also due to the regular before-flood operation of RC. Plots of volume of RC with a suspended layer of peat also relate to silting and also reduce its volume.

Actual specific heat load on the active area of RC does not exceed the calculated value, therefore cooling Δt of circulating water is not lower than the normative value according to the data of TPP. Circulating water in the near water area of the reservoir is cooled by 3–4 °C, which makes ≈50 % Δt. In this case, the specific load on the area of the cooler in this zone is much higher than in the middle or end part of RC. The water area became shallow during the operation period of operation, but this did not affect cooling capacity of RC.

In the catchment area, the surface water temperature is higher by 2.0 °C than in the central part of the reservoir. This is a consequence of a short distance from the place of discharge of circulating water through the channel No. 1, and hence a lack of time to cool it and the smaller active area of RC.

The study results can be useful for operation of reversible water supply systems with RC, namely:

– for redistribution of circulating water of TPP into the head and parts of water area of RC;

– for operation of discharge facilities of RC with flow-through.

The results are useful for project assessment of an operation life of a reservoir-cooler taking into account the effect of silting, as well as determination of a useful volume and active area of RC.

Determining the optimal ratio of discharges of circulating water to the head and into the tail waters of RC taking into account a flow of river water and increase in the minimum thermal load on a reservoir may be the subject of further research.

7. Conclusions

1. Over the 50-year operation period of the flow-through reservoir-cooler, the annual intensity of silting made up 0.2 % of the total volume of RC. The total area of RC decreased by 22 %, however, the active area of RC did not decrease significantly. Due to a reduction in the area of shallow water of RC, the average depth increased by 0.5 m.

2. The presence of significant silting in the tail section of RC did not affect the characteristic process of cooling of circulating water due to the presence of the nearby zone of intensive cooling. A flow-through of the reservoir-cooler contributes to this.

3. We can regulate the hydrothermal mode of a water catchment area of RC both for reducing the temperature of circulating water and for ensuring the maximum acceptable temperature of the river water in the lower water. We proposed the functional dependence for determining water temperatures in a catchment area.

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