Mathematical modelling of operation modes of water intake structures’ cooling reservoirs

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Abstract. The article provides an overview of the tasks of studying heat and mass transfer in reservoirs with hydraulic flows of circulating water from turbine condensers. The conditions of effective reduction of the temperature of the water from the reservoir via a slotted water intake working on the principle of a hydraulic siphon are considered. The scheme of the slotted siphon-type water intake is presented, as well as its technical implementation. The system of differential equations for the numerical calculation of the parameters of cooling circulating water in reservoirs with siphon culverts is designed. An assessment of the effectiveness of the use of hydraulic slit water intakes in the cooling systems of the recycled water of thermal power plants is contained in the conclusion.

1. Introduction

During discharging circulating water into water bodies, which is used to cool the condensers of turbines of thermal power plants, conditions for intensive heat storage must be created. Large power plants with a capacity of 2–3 GW are taken to cool their units to 150 m³/s of water [1]. Therefore, such power plants are located near large reservoirs (reservoirs - coolers), the purpose of which is to obtain additional cooling of the water coolant created by tower evaporative cooling towers. Drainage of hot water and its intake is carried out from the free surface of the reservoir. Due to the fact that the density of water at such temperatures is lighter than the water in the pool, in the course of the flow, in the absence of mixing, the temperature of the incoming hot water manages to decrease only due to evaporation slightly. As a result, at the outlet of the reservoir, the turbine condensers again receive water, the temperature somewhat different from that which was before. The task is to find a way to effectively increase the cooling capacity of the reservoir-cooler [2]. There are studies in which this problem is solved on the basis of hydrodynamic modelling of the location of the water intake structure, while the calculations are performed for various scenarios, which take into account both extreme climatic and technological conditions [3,4]. There some research works which include the development of probabilistic models of the temperature regime and calculation of temperature
stratification for the functioning of the reservoir-cooler for predicting and estimating the temperature of the reservoir-cooler water and the technical water supply system as a whole [5,6]. This study examines a new approach to solving this kind of problem. It is shown that the problem can be solved by installing particular slotted water intake siphon type hydraulic structures. With their help, the output intake of water from the bottom depths from cold water should be provided. Currently, there are no proposals for the designs of such inputs and studies of hydraulic and thermal modes of their functioning.

The aim of the work is to develop principles for increasing the efficiency of water intake hydraulic structures of reservoirs - coolers. To solve the set tasks, a model study was conducted of the operating modes of the water intake structures of pools - coolers, which provide cooling of the recycled water of power plants by optimizing the temperature stratification of water bodies.

The contents of the work performed, including the following sections:
- development of ways to reduce the level of the heat load of water intake from reservoirs - coolers for the efficient operation of power plants;
- the mathematical formulation of equations describing the thermal regime of lakes - coolers;
- carrying out computational studies of the thermo-hydrodynamic characteristics of heat transfer processes in reservoir models using siphon-type intakes with an assessment of their thermal efficiency.

2. Slit-hole siphon-type water intake

Cooling of circulating water of large power plants located on land with nearby rivers and reservoirs, as a rule, is carried out in evaporative cooling towers in addition to evaporative cooling in water bodies [7]. In the summer period, with a relatively small difference in the temperatures of the pre-chilled water in the cooling tower and the air temperature, conditions for under-cooling the water coolant are created because of slight cooling from the surface of the water bodies. To increase the duration of contact of the surface layer of water flows with atmospheric air, the trajectory of the movement of water currents from the point of water entry into the reservoir to the point of intake is expanded. In this case, the desired result of cooling the circulating water at relatively high temperatures and humidity cannot be achieved.

A known method of cooling the circulating water in the reservoir cooler, in which it is proposed to lower the temperature of the withdrawn water by using cold water of the bottom layer [8]. The method includes discharging warm water into a reservoir - a more refreshing, cooling it due to natural processes and taking water from the upper layer of the reservoir-cooler, while a portion of the discharged warm water is supplied to the bottom region of the intake zone through a particular pipeline. The incoming warm water is mixed with the cold water of the bottom layer and heats it, as a result of which the density of the water in the bottom layer decreases, the water rises, where it is taken and fed to the condensers of steam turbines. The disadvantage of this method of cooling water is the high temperature of the made water from the reservoir, since the rise of cold bottom water in the intake zone is carried out by mixing the water of the bottom layer with part of the warm discharge water, as a result of which the cold bottom water is heated, and the temperature of the taken water rises. So there is a task of reducing the temperature of the water taken from the reservoir - cooler during the summer operation of the station without a proper solution.

A method is proposed that will allow reducing the temperature of the taken water from the reservoir - cooler due to cold bottom water, with the heat of the made water being adjusted [9]. Technically, the result is achieved in that the cooling of the circulating water coming from the reservoir for cooling the units of power plants occurs not only due to natural processes but also due to the intake of water from the lower layers of the pool. For this purpose, the water intake zone is fenced off from the rest of the reservoir with a partition, the upper edge of which is located above the water level, and the lower edge is located at its bottom, forming a gap between the barrier and the bottom, through which only cold water enters the bottom zone into the water intake zone. In this case, the temperature of the water taken is regulated by the amount of clearance between the partition and the bottom of the reservoir-cooler.
The implementation of the method of cooling the circulating water in the reservoir cooler is illustrated by the scheme shown in Figure 1 and is carried out as follows.

Water coolant after cooling in the turbine condensers is transported through channel 1 for additional cooling to pond 2, where the temperature goes down because of the surface layer cooling on which is hot water due to stratification. With a slight difference in air and water temperatures on the surface of the pond, cooling of the circulating water to the conditions ensuring the regular operation of the turbines of power plants cannot be achieved. It is proposed to use cold water of the deep layer of the reservoir 4 to significantly reduce the temperature of the water coolant. For this purpose, water intake 6 is blocked off from the rest of the reservoir 2. The upper edge of the dam 7, that dividing the reservoir into two zones, is located above the water level in the main part of the reservoir 2 with uncooled warm water. The lower edge of the dam located at the bottom of the reservoir forms a gap 8. The described construction is actually a hydraulic siphon.

As a result, the warm water of the upper layer 3 is fenced off from the intake zone 6, and when water is taken through the pipeline 5, the water level in the fenced off intake zone 6 decreases, and cold water from the bottom layer 4 passes through the lumen 8 into the intake zone under the action of hydrostatic forces 6. Depending on the size of the clearance 8, water of various temperatures enters the intake zone 6 due to the stratification of the water in the reservoir. By changing the amount of clearance 8, you can adjust the temperature of the water taken.

Figure 1. Diagram of siphon-type slotted water intake.

Thus, fencing off the water intake zone from the rest of the reservoir-cooler by means of a partition with an adjustable clearance between the bottom of the reservoir and the barrier allows the station to use cold water of the bottom layer in summer to lower the temperature of the intake water, while the heat of the intake water is regulated by the amount of clearance between the partition and the bottom of the reservoir cooler.

3. A mathematical model of the thermal stratification of a reservoir with siphon water intakes

The need for mathematical modelling of heat and mass transfer processes in reservoirs and coolers is necessary for a reasonable choice of effective external cooling systems for thermal and nuclear power plants. As a basis for constructing a model of a reservoir with siphon water intakes, methods of mathematical modelling of thermohydrodynamic processes in lakes used to cool the circulating waters of power plants, which were actively developed when creating large-scale power plants [1,10–12], can be taken.

We will use equations to describe thermohydrodynamic processes in water bodies in the form:
\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \] (1)

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} + g \frac{\partial Z_s}{\partial z} = \frac{\partial f_{wx}}{\partial z} \] (2)

\[- \frac{\partial}{\partial z} \left[ (v_T + v_M) \frac{\partial u}{\partial z} \right] + g \frac{\partial P}{\partial x} \frac{\partial u}{\partial z} = f_{u,v} \] (3)

\[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + g \frac{\partial Z_s}{\partial y} = \frac{\partial f_{vy}}{\partial z} \] (4)

\[- \frac{\partial}{\partial z} \left[ (v_T + v_M) \frac{\partial v}{\partial z} \right] + g \frac{\partial P}{\partial y} \frac{\partial v}{\partial z} = -f_{u,v} \] (5)

\[ \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} = \frac{\partial}{\partial z} \left( D \frac{\partial T}{\partial z} \right) \] (6)

Here \( w \) is the vertical velocity component, \( u \) and \( v \) are the horizontal velocity components, \( v_T \) is the turbulent viscosity, \( v_M \) - molecular viscosity \( Z_s \) - mark-free surface, \( \rho \) - density of water, \( \rho = \rho(S,T) \), \( T \) - temperature, \( \rho_o \) - the mean density of water, \( f_{sx} \) and \( f_{sy} \) - projection wave impact forces, \( f_0 \) - average force of wave action.

The following approximations are accepted in the model:
- accelerations during vertical mixing are much less than the acceleration due to gravitational forces, which leads to the admissibility of using the assumption of hydrostatic pressure distribution;
- shear stresses of surface forces in the horizontal plane are much less than the tangential components of the stresses in the vertical plane;
- the values of the difference in water density at different points of the reservoir are much less than the density itself.

For the turbulent viscosity is proposed to use the Prandtl
\[ \nu_T = l^2 \frac{\partial V}{\partial z}, \quad V = \sqrt{u^2 + v^2}, \] (7)

where \( l \) is the length of the mixing path. In the case of homogeneous liquid \( (l = l_h) \) and \( \tau_s = 0 \) (tangent \( \tau_s \) stress on the free surface), we express the path length of the mixing as follows:
\[ \frac{l_h}{h} = 0.14 - 0.08 z_1^2 - 0.06 z_1^4; \quad 0 \leq z_1 \leq 1 \]

where \( z_1 = 1 - \frac{z}{h} \).

In the case where the tangential stresses on the free surface, not zero and there is excitation, this expression can be modified as follows:
\[ \frac{l_h}{h} = a_1 - a_2 z_1^2 - a_3 z_1^4; \quad 0 \leq z_1 \leq 1 \] (8)

\[ z_1 = \frac{z}{h} - z_o \] where: if \( \frac{z}{h} \geq z_o \); \( z_1 = \frac{z}{z_o} \) \( \frac{z}{h} \leq z_o \); if \( \frac{z}{h} < z_o \);

Here \( z_o = \frac{\tau_h}{\tau_o + \tau_s} \); \( a_1 = \alpha h_w + 0.14 \), \( a_2 = \frac{k}{2} - 2 h_w \), \( a_3 = \alpha h_w - \frac{k}{2} \).
Here $\tau_b$ and $\tau_s$ are the tangential stresses at the bottom and free surface, respectively, $h_n$ is the rms wave height, $k = 0.4$ is the Karman constant, $\alpha$ is the numerical coefficient that must be identified during verification.

The boundary conditions on the free surface are set as follows.

On the waterproof border: $u_n = 0$

At the inlet of water to the siphon: if $u_n < 0$, then $\bar{U}$

At the outlet of water from the siphon: if $u_n < 0$, then $U_n$

Here $\bar{U}$ is the modulus of the vector averaged over the depth of speed, $n$ is normal to the free surface, and the normal direction is considered to be positive inside the region.

On the liquid boundary: $z_s = f(t)$

It is known that during the discharge of warm water, density stratification, the so-called thermal stratification, can occur. One of the most effective and at the same time simple methods account for this effect is the change in expression for mixing path lengths as follows: $l_s = l_h (1 - d^{wRi})^{1/4}$, (12)

where $l_h$ and $l_s$ - mixing path length in homogenous and stratified liquid, $d=20, n=1, m = 0.5$ are the parameters determined by calibration according to the data of characteristic experiments, $Ri$ is the gradient Richardson number: $Ri = -\frac{g \cdot \frac{\partial \rho}{\partial z} \cdot l^2}{|f|}$ (13)

With a high level of turbulence, $\nu_f >> \nu_M$, expression (14) becomes the usual expression:

$$Ri = -\frac{g \cdot \frac{\partial \rho}{\partial z}}{\rho \left( \frac{\partial u}{\partial z} \right)^2}$$ (14)

To solve the system of equations, methods and calculation programs described in [10,13] were used.

The parameters of the model basin were selected on a relative scale, similar to the characteristic in-situ reservoir (Table 1).

The results of calculations with the reservoir-cooler model for studying the effect of temperature stratification on the degree of decrease in the temperature of the circulating water leaving the reservoir during water intake from the siphon compartment with a slotted shutter were carried out according to the following scheme. At the first stage of work, calculations were performed in a static model in the absence of incoming and outgoing water from the cooling pool. At the same time, a fixed cooling mode for the bottom of the pool was maintained due to thermostatic of water in the thermostatic pool. The volume of water in the pool - the cooler was set constant at 0.1 m³. Pool water fill temperature – 40 °C. In water circulating in the pool incubator, the temperature was kept constant at values of 10-15 °C. The model experiments were carried out in different temperature points of the more cooling pool at several depths from the surface to the bottom.

| Table 1. Characteristic parameters of the model pool. |
|----------------|-------------|
| Parameter | Value |
| water mirror area, m² | 1.5 |
| water volume, m³ | 0.15 |
| maximum length, m | 1.5 |
| maximum width, m | 1.0 |
| water mirror area, m² | 1.0 |
| average discharge water discharge m³/ s | 0.0005 |
average depth, m 0.1
hot water temperature, °C 40
outlet water temperature, °C 18

The main series of model calculations were performed for the conditions of constant intake and emptying of the pool - cooler and stationary water cooling in the thermostatic pool. The volume of water in the pool - cooler was provided constant while maintaining a water depth of 0.1 m. Filling the basin with water Temperature remained as in the previous series of experiments, a constant equal to 40°C and feed rates of water extraction in the pool maintained at a cost similar Q_{input} = Q_{yield} = 0.1 l/s. The thermostat water had a temperature of 10°C. The slit valve in the siphon during the experiment varied, taking values of a = 0.01 - 0.05 m.

Figure 2. Calculation Dependence of the depth of cooling of the circulating water (ΔT, °C) on the height of the slotted shutter (a) in the siphon compartment of the pool - cooler.

4. Results of mathematical modelling

The efficiency of the intake of chilled water from the lower horizons of the basin through the restrictive opening of the slotted shutter of the siphon compartment is evidenced by an analysis of the results of numerical modelling (Fig. 2).

The highest cooling is achieved on relatively small openings in the slotted shutter. To the lower boundary of the thermocline, the effect of lowering the temperature of the circulating water is steadily manifested. Theoretical calculations are in satisfactory agreement with the observational data and confirm the conclusion reached regarding the extreme depths above which it is impractical to take water from the cooling pool.

The proposed mathematical model for describing the operating modes of the reservoir-cooler is intended for numerical calculations of the temperature fields of the laboratory layout of the reservoir at various hydraulic and thermal loads. The results of the calculations can be used for comparative analysis with the data of experimental studies of the water intake in a small-scale model of a reservoir with a slotted siphon-type water intake operating in full-scale reservoir coolers in order to determine the optimal control modes for temperature stratification, which ensures the efficiency of the depth of cooling of the condenser coolants of power plants turbines [14].

5. Conclusions

Based on the results of model stratification calculations of taking into account transition coefficients of scale similarity, it is established and confirmed:

- The intake of water entering the reservoir on its free surface, open to the atmosphere using a slotted hydraulic siphon, reduces the temperature of the water leaving the reservoir by 1 °C.
Compared with standard cooling of circulating water of power plants in summer period, circulation water with such cooling allows an additional increase in the generation of electric energy to 0.5% [7].

The experiment with the model and the calculation in satisfactory agreement demonstrates the efficiency and real implementation of the optimal temperature control regimes for intake water from reservoirs - coolers using hydraulic siphons installed at the outlet of the reservoirs. The cooling effect of the water fluids of the condensers of power plants taken by siphons from deep waters after circulation transportation to the turbines, achieved at a level of several degrees, can reduce the risks of reducing the growth of power generation during operation in the summer season compared to traditional methods of taking water from the water surface.

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