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NUMERICAL SIMULATION OF HYDROTHERMAL REGIME OF WATER INTAKE OF NPP TO PREVENT ICE IMPEDIMENTS

A. S. Sokolov[1]

ABSTRACT

The problem of providing in winter reliable maintenance of the technical water supply system of NPP with a cooling pond is considered on definite example. To prevent ice impediments in water intake structures a part of water heated by condensers of circulating water is discharged directly into supply canal. As a result of numerical simulation of hydrothermal processes there have been obtained probabilities of ice formation in the cooling pond and determined optimal parameters of water discharge.

One of the most popular types of circulating water coolers of NPP is a natural or artificial reservoir where cooling is happened because of heat exchange with the atmosphere through a free surface. In spite of the fact that in cooling ponds the water temperature exceeds the natural level on the average, at air temperature below zero there could be the situations when a considerable part of the cooling pond is covered with ice. It is especially important when NPP is operating not in full power in particular on the stage of step-by-step putting power-generating units into operation. At that there could be malfunctions of water intake structure operation because of ice blockage of input windows.

Thus to provide reliable operation of NPP in winter it is necessary to evaluate the probability of ice formation in cooling ponds and to develop measures to prevent ice impediments in water intake structures.

Next on the example of the cooling pond of one of NPPs there is given the approach to solve these problems on the base of numerical simulation of hydrothermal processes. Discharge of a part of circulating water heated by condensers directly into the supply canal is considered as a measure to prevent ice impediments in water intake structures.

[1] The B.E. Vedeneev All-Russian Research Institute of Hydraulic Engineering (VNIIG), Gzhatskaya str., 21, St.Petersburg, Russia

To simulate hydrothermal processes in a cooling pond there has been used a 2D numerical model based on decision stationary equations of thermal diffusivity and hydromechanics by the method of finite elements in the Galerkin's formulation [1 – 3 et.al.].

Distribution of water temperature was determined by decision of the thermal diffusivity equation integrated by a vertical coordinate

$$\frac{1}{\rho}\frac{\partial(q_1 T)}{\partial x_1}+\frac{1}{\rho}\frac{\partial(q_2 T)}{\partial x_2}=\frac{\partial}{\partial x_1}aH\frac{\partial T}{\partial x_1}+\frac{\partial}{\partial x_2}aH\frac{\partial T}{\partial x_2}+\frac{\Phi_s}{c\rho}, \tag{1}$$

where $q_k=\int_0^H \rho v_k dx_3, k=1{,}2$ – components of the specific mass flow rate; x_k – coordinates in Cartesian system, at that x_3 – the coordinate along the vertical axis; T – water temperature; v_1 and v_2 – horizontal components of velocity; ρ - water density; H – depth; a – efficient (summarized) factor of thermal diffusivity; Φ_s – density of heat flow on a free surface; c – specific heat capacity of water.

The components of specific mass flow rate q_k were determined by the system of hydromechanics equations

$$\frac{1}{\rho}\frac{\partial}{\partial x_1}\left(\frac{q_1^2}{H}\right)+\frac{1}{\rho}\frac{\partial}{\partial x_2}\left(\frac{q_1 q_2}{H}\right)=-\rho gH\frac{\partial\eta}{\partial x_1}+\tau_{s1}-\tau_{b1}+\vartheta\frac{\partial^2 q_1}{\partial x_1^2}+\vartheta\frac{\partial^2 q_1}{\partial x_2^2}; \tag{2}$$

$$\frac{1}{\rho}\frac{\partial}{\partial x_2}\left(\frac{q_2^2}{H}\right)+\frac{1}{\rho}\frac{\partial}{\partial x_1}\left(\frac{q_1 q_2}{H}\right)=-\rho gH\frac{\partial\eta}{\partial x_2}+\tau_{s2}-\tau_{b2}+\vartheta\frac{\partial^2 q_2}{\partial x_1^2}+\vartheta\frac{\partial^2 q_2}{\partial x_2^2}; \tag{3}$$

$$\frac{\partial q_1}{\partial x_1}+\frac{\partial q_2}{\partial x_2}=0, \tag{4}$$

where η - changing of the position of a free surface level; τ_{sk} and τ_{bk} – components of friction tension on a free surface and at the bed correspondingly; g – free fall acceleration; ϑ – summarized coefficient of viscosity.

The components of friction tension on the free surface and at the bed were calculated by the formulas:

$$\tau_{s1}=c_f\rho_a W^2\cos\theta; \tag{5}$$

$$\tau_{s2}=c_f\rho_a W^2\sin\theta; \tag{6}$$

$$\tau_{b1} = \frac{gq_1(q_1^2 + q_2^2)^{1/2}}{\rho C^2 H^2}; \tag{7}$$

$$\tau_{b2} = \frac{gq_2(q_1^2 + q_2^2)^{1/2}}{\rho C^2 H^2}. \tag{8}$$

where c_f – the coefficient of wind tension; ρ_a – air density; W – wind speed; θ - the angle between wind direction and axis x_1; C – Chezy coefficient.

Heat flow density on the free surface was calculated using the dependencies given in [4 – 5]. The roughness factor and other parameters of the mathematical model were given in accordance with the recommendations in [6 – 8].

Modeling of hydrothermal processes was carried out for cooling pond and for the supply canal of NPP: in the first case – with the aim to evaluate possibilities of ice formation at different operation conditions, in the second one – to choose the site of heated water discharge and to determine water flow rate necessary to prevent ice impediments in water intake structures. Operation of one and two energy-generating units of NPP was considered.

At modeling of hydrothermal regime of a cooling pond the boundary conditions for the equation (1) were given with taking into account the fact that the difference between the temperature of the discharged heated water and the water temperature in water intake structure of the power plant was equal to specified difference of temperatures at the inlet and outlet of the condensers of the turbines ΔT, but at the inlet into the supply canal the diffusive heat transfer was considerably lower than the convective one. The component of heat flow normal to the firm soil part of the bank profile was supposed to be equal to zero. The boundary conditions for the hydromechanics task took into account discharge and intake of circulating water at the water discharge and water intake structures of NPP as well as impermeability of the firm soil bank profile for a liquid flow.

Changes of water temperature by the vertical were not taken into account because, as it had been shown by corresponding evaluations, in this case the vertical temperature stratification could not be significant because of wind mixing.

Difference of temperatures at the inlet and outlet of the condensers ΔT was taken equal to 13ºC, circulating water flow rate (circulating flow rate) for one energy-generating unit Q – 34,5 m^3/s.

Influence of ice cover formation on circulating flow changing was taken into account in numerical experiments. If in the result of calculations it was appeared that a part of the free surface of the reservoir was covered with ice the calculation was repeated, taking into account circulation conditions, so many times until there was obtained the acceptable precision of the evaluation of the ice edge position. At that it was supposed that the ice cover boundary coincides with zero isotherm of water temperature.

Isotherm distributions in a cooling pond received in two numerical experiments differed by wind direction are shown as an example in Fig. 1. The calculations were carried out for average long-term meteorological conditions of the coldest month of a year. As it can be seen the wind direction considerably influences on the polinya location in a cooling pond.

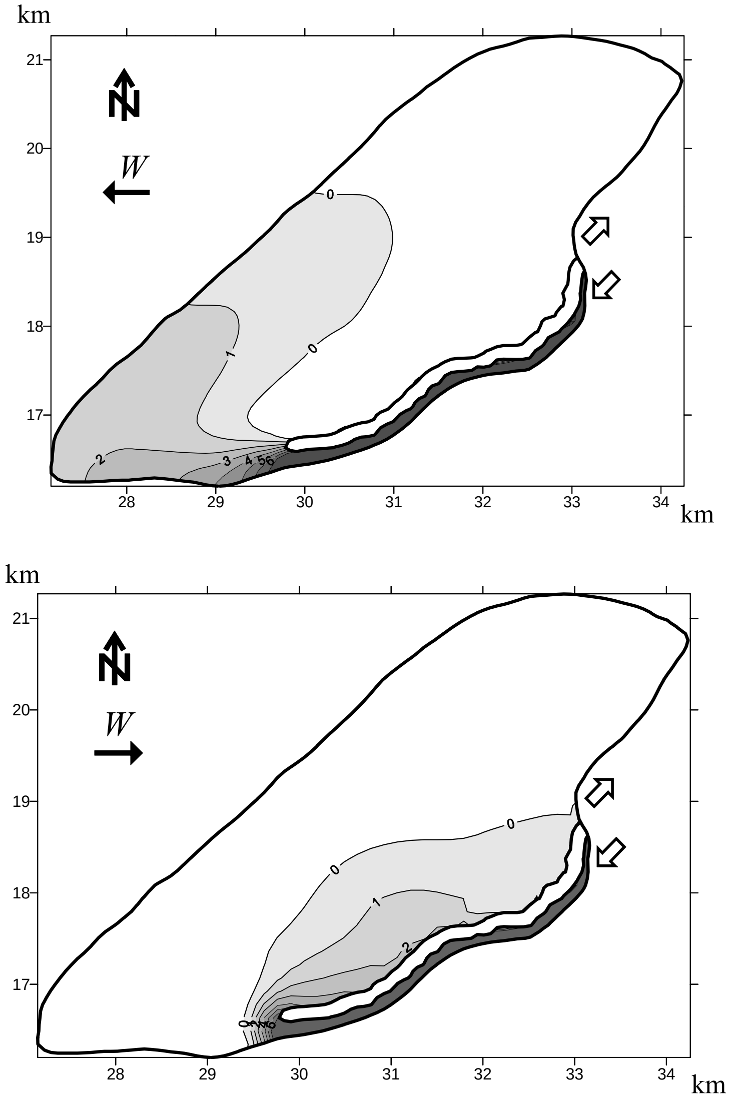


Fig. 1. Temperature distribution in a cooling pond at operating of one energy-generating unit of NPP, obtained in numerical experiments at different wind directions (shown by the arrow with the mark *W*)

Numerical experiments demonstrated that both at operation of one and two energy-generating units of NPP it is quite possible the formation of ice cover in a cooling pond. Quantitative probabilistic evaluation of ice formation around a supply canal and, as a consequence, ice impediments at maintenance of water intake structures were fulfilled taking into account long-term observations of meteorological factors.

On the first stage using numerical experiments there were determined meteorological conditions at which around the inlet of the supply canal the water temperature decreases up to 0ºC. Then taking into account the data of long-term observations of meteorological factors there was determined the probability to realize these conditions and the probability of ice formation in the supply canal.

The results of the stochastic forecast made up in such a way showed that the probability of ice formation in the supply canal of NPP at one energy-generating unit operation is near 1, but at two energy-generating units operation – several times less, however, is also considerable. That is why the numerical modeling of hydrothermal processes in a supply canal was carried out for the cases of one and two energy-generating unit operation.

It was suggested that the grate of physical protection installed in the middle part of the canal, holds ice formations coming with circulating water. That is why the hydrothermal regime has been calculated only for the canal section from the grate up to water intake structures.

At formulation of boundary conditions for the equation (1) it was supposed that the temperature of water flowing through the grate of physical protection is equal to 0ºC. Besides, as at modeling of a cooling pond it was taken into account that the difference between heated circulating water discharging into the canal and the temperature of water coming into water intake structures of NPP is equal to the difference of temperatures at the inlet and outlet of the condensers ΔT.

Flow rate of water running through the grate of physical protection was given equal to the difference between the flow rate of circulating water coming into water intake structures and the flow rate of heated water discharging into the supply canal.

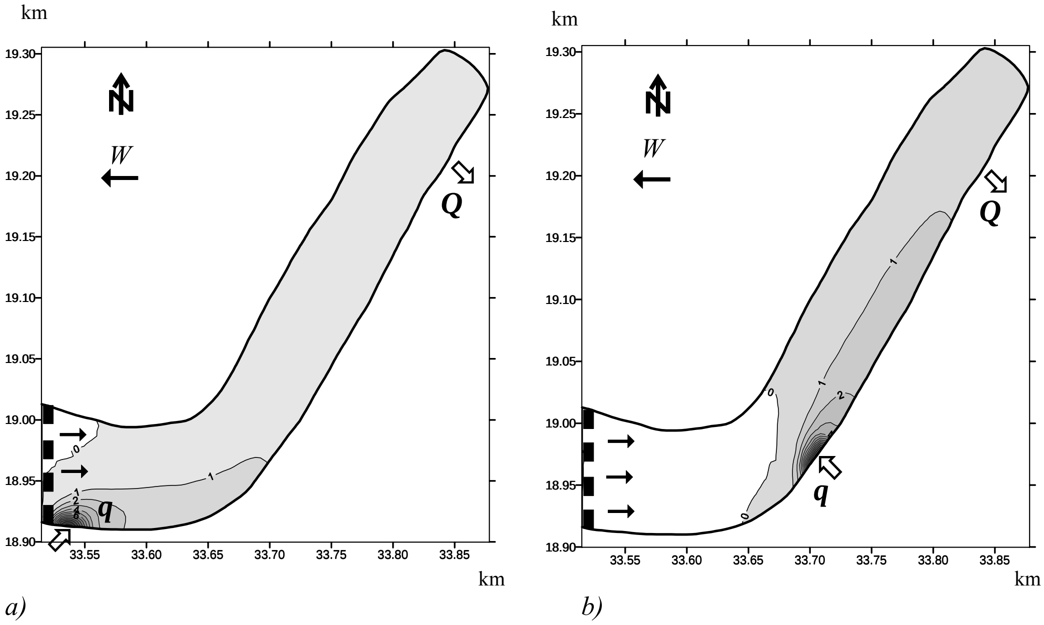
In numerical experiments it was studied the influence of different factors on hydrothermal regime of the supply canal: the site of heated water discharge and its flow rate q, wind conditions, intensity of heat exchange with the atmosphere, probable frazil ice formation at the observed section of the canal.

Some results of numerical modeling for average long-term meteorological conditions of the coldest month of a year are given in Fig. 2 – 3.

At determining the demanded heated water flow rate q_d it was supposed that ice impediments could not appear around water intake structures at the temperature T_{wi} exceeding 1ºC. Thus the flow rate q_d was determined out of the condition that T_{wi} = 1ºC using the dependence $T_{wi} = f(q)$ obtained by the results of numerical modeling.

For the case of frazil ice formation on the considering canal section the demanded flow rate of heated water was calculated by the formula

$$q'_d = \frac{c\rho q_d T_{dis} + KQ_{fi}\rho_{fi}}{c\rho T_{dis}}, \tag{9}$$



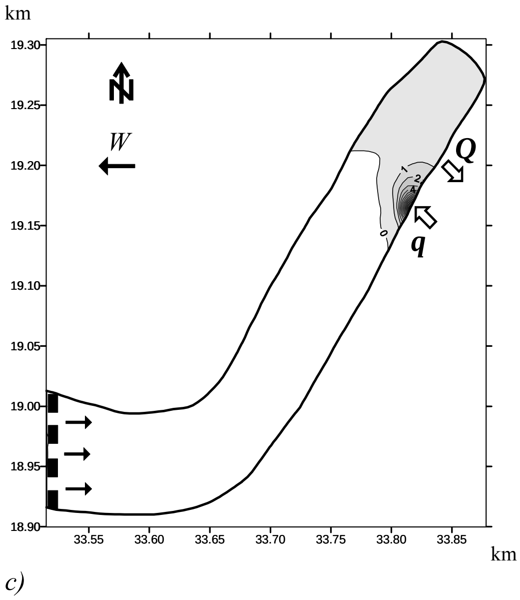


Fig. 2. Temperature distributions in the supply canal of NPP when one energy-generating unit is operating and q=1m^3/s obtained in numerical experiments with different locations of heated water discharge:
a – at the grate of physical protection; *b* – at the distance of 200 m from the grate;
c – at water intake structure of NPP

where q_d – the demanded heated water flow rate when frazil ice does not form in the supply canal; T_{dis} – the temperature of heated circulating water that is supplied into supply canal; K – latent ice melting heat; Q_{fi} – frazil ice flow rate; ρ_{fi} – frazil ice density.

Frazil ice flow rate and density were determined according to recommendations [9 – 12]*.

Numerical experiments showed that changing of intensity of heat exchange with the atmosphere on the considering section of the supply canal influences slightly on changing of its temperature regime because of relatively small area of heat exchange surface.

∗ Calculations of frazil ice drifting parameters were carried out by G.A.Tregub.

However the meteorological conditions influence significantly on frazil ice amount that can form in the supply canal if water becomes too cold.

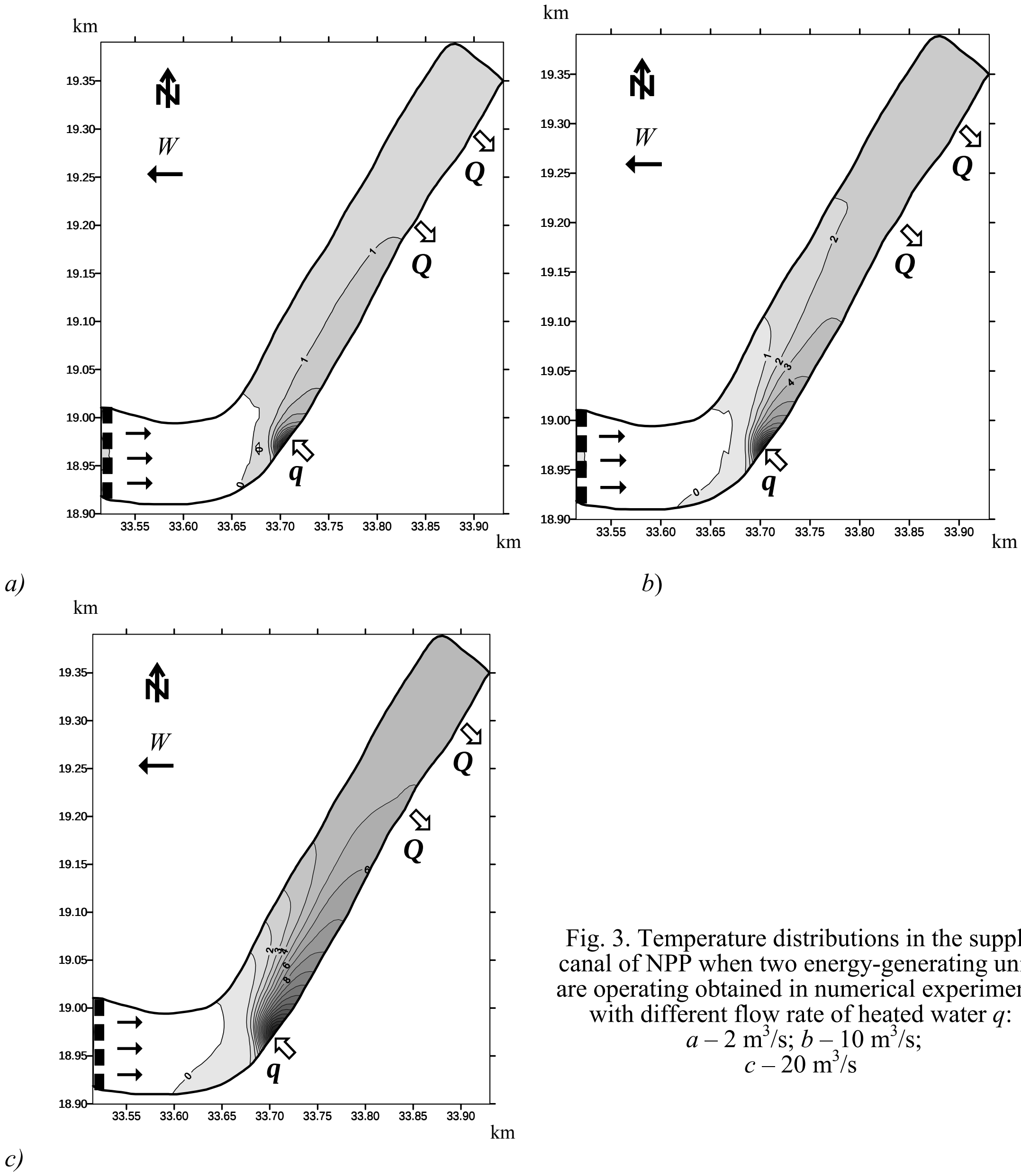


Fig. 3. Temperature distributions in the supply canal of NPP when two energy-generating units are operating obtained in numerical experiments with different flow rate of heated water *q*: *a* – 2 m^3/s; *b* – 10 m^3/s; *c* – 20 m^3/s

Besides, from the results of calculations carried out for different wind conditions it is followed that the wind can influence considerably on hydrothermal regime of the supply canal at the expense of its acting on the water velocity field. The wind promoting distribution of discharging heated water around the line bank where the water intake structures of NPP are located is the most favorable from the point of view to exclude ice impediments.

Bringing near the site of heated water discharge to water intake structures ambiguously influence on its flow rate necessary to prevent ice impediments. From one side, heat losses decreases because of heat exchange with the atmosphere; from another side, it is increased the amount of frazil ice that can be formed on the considered canal section. Besides, at heated water discharge near pumping plants there can appear circulation at which cold water out of a deadlock canal section comes into water intake structures of NPP.

That is why the smallest values of q_d were received for the variants of location of heated water discharge at some distance from water intake structures. In this case if one energy-generating unit is operating the demanded heated water flow rate is from 3 to 4,5% from the circulating flow rate Q in dependence of the wind direction. If frazil ice forms on the considered canal section because water has become too cold the flow rate q_d increases about 10% at average long-term conditions of winter months.

When two energy-generating units are operating and there is no frazil ice in the canal the flow rate q_d is 4 – 4,5% from the total circulating flow rate $2Q$, but if frazil ice is forming – 4,5 – 5%.

It should be noted that if heated water is discharged at the physical protection grate or near water intake structures the values of q_d determined by the results of numerical experiments appeared to be significantly higher. This indicates that it is very important to forecast hydrothermal processes to substantiate winter regime of technical water supply systems of NPP.

The given example demonstrates clearly the possibilities to use numerical simulation on all stages of solving the problem of struggle with ice impediments in water intake structures of thermal and nuclear power plants – from evaluation of ice formation probability in a cooling pond up to development of preventive measures.

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