The calculation of technogenic thermal pollution zones in large water reservoirs

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Abstract. In this paper we present the results of numerical simulation of the processes occurring in cooling reservoirs. The goal of the work is to analyze the possibility of predicting the degree of exposure to thermal discharges under different conditions. The study is performed using one of the largest thermal power plants in Europe – the Permskaya Thermal Power Plant (Permskaya TPP) as an example. The computational scheme that combines 2D and 3D approaches is implemented.

1. Introduction

Today, reservoirs are the most widely used type of coolers for large thermal electric power stations. Their exploitation often meets considerable problems peculiar to a particular basin [1-3]. For small cooling basins the problems are associated with the limitation of power station performance related to a rise of the temperature of water taken off from the reservoir [4], while for large coolers the problems are related to thermal pollution, changes in the ice-thermal regime, hydrophysical and hydrobiological processes, especially in the regions of heated water discharge [5, 6]. Key to the solution of a wide range of technological and ecological problems is getting comprehensive and reliable estimates of the parameters of temperature fields generated by these discharges depending on a set of technological and hydrometeorological parameters [7, 8].

However, numerous data of field observations strongly suggest the need for revising the formulation which is based on the two-dimensional representation of the examined fields and homogeneity of the depth distribution of water temperature. Therefore, to obtain reliable results it is necessary to use a 3D model. In [9-11], the problems of thermal pollution are solved in the framework of such models.

In the present paper, with reference to the Permskaya Thermal Power Plant (TPP) (Permskaya GRES), which is one of the most powerful thermal power plants in Europe, we investigate the temperature fields generated due to discharge of heated waters depending on technological and hydrometeorological parameters.

2. Two-dimensional computational technique

A computer-based hydrodynamic model of the Kama Reservoir in the Dobryanka city region in the two-dimensional approximation was constructed using a licensed, specialized, hydrological software package SMS v.11.1 (Surface-waterModelingSystem), designed to simulate hydrodynamics, the
propagation of pollution (including temperature) and sediment transport in a water body within the framework of a two-dimensional approximation.

The SMS v.11.1 package uses the finite element method to discretize the Navier-Stokes Reynolds-averaged equations to describe turbulent flows. The friction is calculated by the Manning or Chezy formula.

For the description of flow, momentum and mass conservation equations, averaged over the depth, are solved:

\[ h(\partial u/\partial t) + hu(\partial u/\partial x) + hv(\partial u/\partial y) - h \rho \left[ E_\alpha \left( \partial^2 u/\partial x^2 \right) + E_\beta \left( \partial^2 u/\partial y^2 \right) \right] + gh \left[ \partial a/\partial x + \partial h/\partial x \right] + \]

\[ g \nu n^2 h^{-1/3} \left( u^2 + v^2 \right)^{1/2} - \zeta V^2_a \cos \psi - 2hn\omega \sin \Phi = 0, \]

(1)

\[ h(\partial v/\partial t) + hv(\partial v/\partial x) + hu(\partial v/\partial y) - h \rho \left[ E_\alpha \left( \partial^2 v/\partial x^2 \right) + E_\beta \left( \partial^2 v/\partial y^2 \right) \right] + gh \left[ \partial a/\partial y + \partial h/\partial y \right] + \]

\[ g \nu n^2 h^{-1/3} \left( u^2 + v^2 \right)^{1/2} - \zeta V^2_a \sin \psi + 2hu\omega \sin \Phi = 0, \]

(2)

\[ \partial h/\partial t + h(\partial a/\partial x + \partial h/\partial y) + u(\partial h/\partial x) + v(\partial h/\partial y) = 0, \]

(3)

where \( h \) is the depth, \( x, y, t \) are coordinates and time, \( u, v \) are \( x \) and \( y \) components of velocity, respectively, \( \rho \) is the water density, \( E \) is the turbulent viscosity coefficient, \( g \) is the gravity acceleration, \( a \) is the base elevation (bottom), \( n \) is the Manning roughness, \( \zeta \) is the empirical coefficient of horizontal wind deflection, \( V_a \) is the wind speed, \( \psi \) is the direction of the wind, \( \omega \) is the coefficient of the Earth's rotation angle and \( \Phi \) is the latitude.

Equations (1)–(3) are solved by the finite element method, using the Galerkin method of weighted residuals. Elements on sections of the channel can be linear (one-dimensional) or square (two-dimensional) quadrangular, or triangular, and can have curved (parabolic) sides. The form of the basis functions is quadratic for the velocity and linear (one-dimensional) or square (two-dimensional) quadrangular, or triangular, and can have curved (parabolic) sides. The form of the basis functions is quadratic for the velocity and linear for the depth. The spatial integration is performed by Gaussian integration. The second derivatives with respect to time are replaced by a nonlinear approximation of the finite difference. It is assumed that functions that depend on time have the form of a polynomial of the \( c \) order of time in a given interval:

\[ f(t) = f(t_0) + at + bt + ct^c, \quad t_0 \leq t \leq t_0 + \Delta t, \]

(4)

here \( a, b \) and \( c \) are the constants. Note that, based on experiments, the best value for a constant \( c \) is 1.5. The solution is sought by an implicit scheme, the system of nonlinear equations is solved by the iterative scheme of Newton-Raphson.

The equation averaged over the depth, describing the heat transfer process, has the form:

\[ h(\partial T/\partial t + u(\partial T/\partial x) + v(\partial T/\partial y)) - \partial \left( D_\alpha (\partial T/\partial x) \right)/\partial x - \partial \left( D_\beta (\partial T/\partial y) \right)/\partial y + k(T_{\text{atm}} - T) = 0, \]

(5)

where \( h \) is the flow depth, \( T \) is the water temperature, \( D_\alpha, D_\beta \) are the turbulent mixing coefficients, \( k \) is the coefficient characterizing the intensity of the thermal interaction in the "atmosphere – water surface" system.

For the most complete and effective specification of the morphometry features of the Kama reservoir, a rectangular–triangular mesh consisting of approximately 28000 elements (nodes) with an average rib length of the element of 50 meters was constructed in the calculational domain. The main characteristic dimensions of the simulated object are 20 km in length, and from 1.5 to 4 km in width.

3. Three-dimensional computational technique

The 3D hydrodynamical model was built for the reservoir part with linear dimensions of 1000 m adjacent to the Perm TPP and including the points of water intake and water discharge. Software package ANSYS Fluent was used for the 3D simulations at the computer cluster URAN of the IMM
UB RAS. The problem was solved in the framework of a non-stationary non-isothermal approach on the basis of the \( k-\varepsilon \) model describing turbulent pulsations. We implement the Reynolds-averaged Navier-Stokes equations:

\[
\frac{\partial \rho}{\partial t} + \left( \frac{\partial (\rho u_i)}{\partial x_i} \right) = 0,
\]

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_i} \right) \right) \right] - \frac{1}{\rho} \frac{\partial \left( \rho u_i \varepsilon \right)}{\partial x_j} \frac{\partial \varepsilon}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_i} \right) \right) \right] \frac{\partial \varepsilon}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_i} \right) \right) \right] \frac{\partial \varepsilon}{\partial x_j} + \rho g_i.
\]

Here, \( \rho \) is the density, \( x \) and \( y \) are coordinates (we use Cartesian coordinate system), \( u_i \) are the velocity components, \( \mu \) is the kinematic viscosity, \( \mu_t \) is the turbulent viscosity.

The turbulence kinetic energy \( k \) and rate of its dissipation \( \varepsilon \) are obtained from the following transport equations:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + \frac{\rho \varepsilon}{\sigma_k} - \frac{\rho e}{\sigma_k},
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\mu} \varepsilon \left[ k \right] - C_{\varepsilon} \frac{\rho e^2 k}{\sigma_\varepsilon}.
\]

In equations (8)-(9), \( G_k \) represents the generation of turbulence kinetic energy due to the mean velocity gradients \( G_k = \mu S^2 \) where \( S \) is the modulus of the mean strain rate tensor, defined as \( S = \sqrt{2 S_{ij} S_{ij}} \), \( S_{ij} = 0.5 \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \), \( G_k \) is the turbulence kinetic energy due to buoyancy, which is calculated as

\[
G_k = g_i \left( \beta \mu_t Pr^{-1} \frac{\partial T}{\partial x_i} \right),
\]

where \( \mu_t \) is the turbulent viscosity determined as: \( \mu_t = \rho C_{\mu} k^2 / e \), where \( C_{\mu} \) is a constant.

Simulation of turbulent heat transfer is performed using the Reynolds model similarly to that of turbulent momentum transfer. Hence, the equation of energy is expressed as

\[
\frac{\partial (\rho E)}{\partial t} + \frac{\partial (\rho u_i E)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial E}{\partial x_j} \right] + \left( k_{\text{eff}} \frac{\partial T}{\partial x_j} \right) + u_i (\tau_{ij})_{\text{eff}} ,
\]

where \( E = h + \frac{p}{\rho} \) denotes total energy, \( h = C_T T \) denotes system enthalpy, \( k_{\text{eff}} \) denotes effective thermal conductivity, and \( (\tau_{ij})_{\text{eff}} \) is the stress tensor deviator defined as

\[
(\tau_{ij})_{\text{eff}} = \mu_{\text{eff}} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_i} \right) \right) \frac{\partial \varepsilon}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_i} \right) \right) \right] \frac{\partial \varepsilon}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial}{\partial x_i} \left( \frac{\partial u_i}{\partial x_i} \right) \right) \right] \frac{\partial \varepsilon}{\partial x_j} + \rho g_i.
\]

The model constants \( Pr_{\varepsilon}, G_{k}, C_{2x}, C_\mu, \sigma_k \) and \( \sigma_{\varepsilon} \) were taken to have the following values:

\( Pr_{\varepsilon} = 0.85 \), \( C_{2x} = 1.44 \), \( C_\mu = 1.92 \), \( C_\mu = 0.09 \), \( \sigma_k = 1.0 \), \( \sigma_{\varepsilon} = 1.3 \).

Boundary conditions imposed on the edges of the computational domain were as follows. At the bottom and at the banks the no-slip conditions and fixed temperature were imposed: \( u_i = u_i = u_i = 0 \), \( T = T_0 \).

At water intake and water discharge points, the water velocity and temperature were taken to be constant: \( u_i = V_{\text{intake}}, T = T_0 \) at the input channel inlet and \( u_i = V_{\text{entrance}}, T = T_{\text{entrance}} \) at its outlet. The upper boundary of the fluid was assumed to be free of tangential stresses. To take into account the wind stress at the river surface we used the formula \( \tau = \rho_{\text{air}} C W^2 \) presented in the work by Wu [12], where \( \rho_{\text{air}} \) is the air density, \( C \) is the dimensionless wind stress coefficient, and \( W \) is the wind speed at 10 m above the water surface. According to this formula, for \( 1 \text{ m/s} < W < 15 \text{ m/s} \) we have \( C = 0.0005 W^{0.5} \). In the calculations we used the value \( C = 1.41 e^{-03} \) for \( W = 8 \text{ m/s} \).
4. Results of calculations

The calculations were carried out for the following meteorological and hydrological characteristics of the Kamsky reservoir and technological characteristics of Permskaya TPP: the water discharge in the discharge channel of Permskaya TPP when three power units are operating is $85.3 \ m^3/s$; the flow rate at the Kama Reservoir is $850 \ m^3/s$; the flow rate at the Tyus River is $4 \ m^3/s$; the flow rate near Dobryanka city is $12 \ m^3/s$; the water level at the Kamsky reservoir is $108.5 \ m$; water temperature in the discharge channel of Permskaya TPP is $40^\circ C$; background water temperature in the Kama Reservoir is $15^\circ C$; the wind is southeast, the average wind speed is $8 \ m/s$; the period of time covered in the calculations is 5 days.

The computational domain for two-dimensional calculations was constructed taking into account the tributaries of the Kama River. Morphometry and the extent of the area under consideration in 2D approach are shown in Figure 1.

Figure 2 shows the velocity field in the Kama Reservoir, obtained in the calculations for the case where three power units are operating at Permskaya TPP and the wind direction is opposite to the flow of the river. As one can see, warm waters are shifted to the left bank and move upwards, towards the supply channel, which leads to the increase in the temperature of the water being taken. As follows from the results of two-dimensional calculations, the heated water reaches the supply channel in 11-12 hours. The period of running up to the water intake devices (pumping station) is approximately 19 hours. In turn, near Dobryanka city the water temperature does not change. Data on the velocity distribution, obtained in two-dimensional calculations, were used as the boundary conditions for the velocity at the inlet cross-section of computational domain in three-dimensional modeling.

![Figure 1. The scheme of the Kama reservoir part covered in the 2D calculations, the boundaries of the domain considered in three-dimensional modeling are shown by red lines.](image-url)
Figure 2. The velocity distribution field in the Kama Reservoir in the case of operation of three power units at Permskaya TPP.

Figures 3a-3c show the velocity vector fields at different horizons (depths) obtained in 3D calculations. In the surface layer, the flow structure is completely determined by the wind effect and directed against the movement of runoff currents. The average velocity is \( \sim 0.2-0.3 \text{ m/s} \). Principal changes in the flow structure occur at a depth of 4-5 m and a pronounced three-dimensional vortex is observed in the lower part of the section, whose influence extends to a depth of 9 m. In addition, it affects the distribution of the temperature field, forming the "3D-tongue" at the bottom of the simulated domain.

5. Conclusion

For the scenario considered in the calculations, the maximum thermal effect is observed. The increase in temperature with respect to background values by 3 and 5°C, respectively, takes place in the water area of 2.8 and 1.5 km².
Figure 3. The velocity vector field in the surface layer of the Kama Reservoir: (a) velocity vector field in the surface layer of the Kama reservoir, (b) at a depth of 5 m, (c) at a depth of 10 m, (d) temperature field (°C) in the surface layer of the Kama reservoir

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