Computer simulation of thermal processes in water bodies under different hydrometeorological conditions

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Abstract. 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 waste water discharges taking into account a set of technological and hydrometeorological parameters. In this work, the problem under consideration is analysed, using as an example the Magnitogorsk Iron and Steel Works (MMK), one of the world's largest steel producers and a leading Russian metal company. The discharge channels of MMK drain warm water in the Magnitogorsk reservoir of the Ural River.

1. Introduction

At present, the relationship between power and water resources is the burning issue of the renovation projects for water supply systems of many industrial plants. A rapid development of the industrial sector led to an increase in electric power demands. A successful implementation of this task implies the reconstruction of existing and the creation of new thermal power plants and nuclear power stations with a marked increase of their power generation capacity, which is naturally associated with a significant increase in the volume of cooling water required for their operation. For economy and safety reasons most power plants are located in the coastal zones and operate on permanent watercourse systems, in which water is taken directly from the reservoirs that act as coolers. At such plants, a thermal plume heated to high temperatures is emitted into the atmosphere and is carried directly into the reservoir [1, 2]. A huge amount of heated water is discharged into the receiving reservoir, which causes the natural temperature of the receiving water to increase. This has a direct or indirect effect on the ecological status of the water environments known as thermal effects [3]. This is the reason why the relationship between power and water resources is considered to be the problem at the focus of researchers; attention [4–8]. Different research methods are aimed at solving the problems of thermal pollution. The spread of the heat spot released by shore-based power plants is usually controlled by measuring the water temperature at the observation points. Although the measurement data obtained by this method are highly accurate, this method also requires large resources, since due to the limited sample size the method yields only discrete data, which cannot reflect the spatial change in the effect of the thermal plume [9]. An important research method is numerical simulation, which is necessary for understanding the effects produced on the environment by thermoelectric power plants [2, 10].
A three-dimensional numerical simulation of turbulent mixing of water masses at different temperatures was carried out in [13–15] in the framework of the LES turbulence model described in [11,12] by solving the Navier-Stokes equations. Modelling of great water masses was accomplished with the use of the parallel computation technique. It was shown that the computation time depends on the number of grid nodes and processors.

In this paper, the hydrodynamic models of the surface layers of water bodies were developed based on the three-dimensional numerical modelling [2, 16-18]. The numerical calculations were performed for the environmental conditions of the Magnitogorsk Iron and Steel Works (Magnitogorskiy Metallurgicheskiy Kombinat, abbreviated as MMK). Hot water from this plant is discharged directly into the Magnitogorsk reservoir of the Ural River. The study was carried out for different technological and hydrometeorological conditions.

2. Computational technique.
The 3D hydrodynamical model was built for the part of Magnitogorsk reservoir with linear dimensions of 2000 m adjacent to the MMK and including the locations of water intake and water discharge channels to/into the cooling pool (Fig.1). The Magnitogorsk Iron and Steel Works discharges warm waste water through the special channels directly into the Magnitogorsk reservoir of the Ural River.

![Figure 1](image1.png)

**Figure 1.** Scheme of the object under study. The MMH location map including the area of the Magnitogorsk reservoir (a). Computational domain diagram (b).

The ANSYS Fluent software package was used to make 3D simulation on the computer cluster URAN at the IMM UB RAS. The problem was solved in the framework of the $k-\varepsilon$ model describing turbulent pulsations based on the non-stationary non-isothermal approach. We use the Reynolds-averaged Navier-Stokes equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0$$

(1)
\[ \frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_l}{\partial x_l} \right) \right] + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{2}{3} \rho k + \mu_i \frac{\partial u_i}{\partial x_j} \delta_{ij} + \rho g_i \]  

(2)

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

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

\[ \frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho ku_j) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_i}{\sigma_k} \right] \frac{\partial k}{\partial x_j} + G_k + G_b - \rho \varepsilon \]  

(3)

\[ \frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_i}{\sigma_\varepsilon} \right] \frac{\partial \varepsilon}{\partial x_j} + C_{\varepsilon} \frac{\varepsilon}{k} (G_k + C_{\varepsilon} \varepsilon) - C_{\varepsilon} \rho \varepsilon^2 \]  

(4)

In equations (3)-(4), \( G_k \) represents the generation of turbulence kinetic energy due to the mean velocity gradients \( G_k = \mu \sigma_k^2 \) where \( S \) is the modulus of the mean strain rate tensor, defined as \( S = \sqrt{2S_{ij} S_{ij}} \), \( S_{ij} = 0.5 (\partial u_i / \partial x_j + \partial u_j / \partial x_i) \), \( G_b \) is the turbulence kinetic energy due to buoyancy, which is calculated as

\[ G_b = g_i \left( \beta \frac{\mu}{\Pr} \frac{\partial T}{\partial x_i} \right) \]  

(5)

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

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

\[ \frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_j}[u_j(\rho E + p)] = \frac{\partial}{\partial x_j} \left[ k_{\text{eff}} \frac{\partial T}{\partial x_j} + u_i (\tau_{ij})_{\text{eff}} \right] \]  

(6)

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

\[ (\tau_{ij})_{\text{eff}} = \mu_{\text{eff}} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu_{\text{eff}} \frac{\partial u_k}{\partial x_k} \delta_{ij} \]  

(7)

The model constants \( \Pr, \ G_{ie}, \ C_{2e}, \ C_{\mu}, \ \sigma_k \) and \( \sigma_\varepsilon \) were taken to have the following values [19]: \( \Pr = 0.85, \ C_{ie} = 1.44, \ C_{2e} = 1.92, \ C_{\mu} = 0.09, \ \sigma_k = 1.0, \ \sigma_\varepsilon = 1.3. \)

The spatial discretization scheme of second-order accuracy was applied. Simulation of temporal evolution was carried out using an explicit second-order scheme.

The boundary conditions at the edges of the computation domain were taken as follows. At the bottom and at the banks of the reservoir the no-slip conditions and fixed temperature were imposed: \( u_1 = u_2 = u_3 = 0, \ T = T_0 \).
At the inlet of the computational domain the main flow velocity was assumed to have one nonzero component, which was invariable over the inlet cross-section, and the temperature was assumed to be equal to the background temperature of the reservoir water: \( u_i = V_i, \ T = T_0 \).

At water intake and water discharge points, the water velocity and temperature were assumed to be constant: \( u_i = V_{\text{intake}}, \ T = T_0 \) at the entrance of the discharge channel and \( u_i = V_{\text{entrance}}, \ T = T_{\text{entrance}} \) at the exit of the channel. The upper boundary of the fluid was free and non-deformable, and the effect of wind was taken into account through the evaluation of the tangential stresses by the Ekman formula [20]. Heating of the water surface by the surrounding air was estimated by applying the linear heat transfer law and the heat transfer coefficient was selected based on the analysis of the in-situ measurement data.

The computational grid was generated using the Gambit 2.4 package of ANSYS Fluent. The number of nodes through the depth of the computational domain was taken to be 21. The non-uniform grid was constructed using the bottom morphometric data obtained from the in-situ measurements in 2014. In the horizontal direction, the computational grid consisted of tetragonal elements distributed uniformly along the entire length, with the characteristic linear size of 20m. The computational grid included 400 hundred thousands of nodes.

The complex geometry of the computational domain was simulated in the following way. To adapt the morphological data available in the coordinate-depth format to the capabilities of the mesh generator, the bottom of the reservoir was represented as a set of simple geometrical objects of some specified resolution, which were then introduced into the file. Based on the array of data describing the reservoir bottom morphology, a code was written to produce a batch file for the grid generator of the ANSYS Fluent package. The proposed code is of general character and can be applied to the construction of similar geometries and to other tasks.

3. Formulation of the problem

The Magnitogorsk Metallurgical Works is currently implementing a set of environmental initiatives aimed at reducing the man-made impact on water bodies. In the near future, the company plans a complete elimination of water draining into the Magnitogorsk reservoir. At present, according to this plan, the MMK is completing the implementation of the main phase of the project for the reconstruction of the circulating water supply system including the expansion of the cooling reservoir. The project envisages the construction of a dam separating the reservoir from the influence of the MMK circulating water supply system. This will stop the discharge of waste waters from the cooling reservoir to the Magnitogorsk reservoir. Completion of the construction and installation works is scheduled for the end of October. In parallel, works on the formation of the dam crest are currently under way. Considerable efforts are being made to arrange its landscaping and stocking the reservoir with fish. The purpose of this work is to assess the parameters and modes for monitoring the process of water cooling during the operation of the MMK in the presence of the dam. The problem was solved within the framework of the model described in [2]. This model can be applied to the above problem because its thermal and hydrodynamic characteristics are identical to those used in [2] for estimating the zones of thermal pollution formed in the Kama reservoir due to discharges of waste waters of the Permskaya GRES.

Numerical simulation was carried out for the model scenario. The objective of the numerical simulation in the context of the proposed scenario was to determine the operating capacity of the water intake stations during the hottest summer months at temperatures not exceeding 28 °C when using the circulating water supply system.

According to the field surveys conducted in 2018, it was found that the bottom water temperature of the Magnitogorsk reservoir in the region of the culvert unit does not exceed 23 °C. The water temperature at the waste water outlet №1 was taken equal to 300°C at the discharge flow rate of
11.6 m$^3$/s, and at the outlet №2 – 40 °C at the discharge flow rate of 3.7 m$^3$/s. The flow rate through the culvert was taken to be 3.9 m$^3$/s.

The computation was made taking into account the interaction between the water mass and atmosphere temperatures. The data used were based on the decadal maximum air temperature, which was observed in the 2nd decade of July 2012 and was equal to 25.3 °C under calm conditions.

In addition to water temperature, the results of model calculations in 3D could be used to evaluate the dynamics of heat fluxes in the water area and the depth of the cooling tank.

4. Computational Results

The results of simulation presented below are the outcome of a rather cumbersome process, associated not only with the specifics of setting the initial information and building an adapted computational grid, but also with the computation process itself. In particular, to obtain a relative stationary behavior of flows under the existing multi-factor conditions, the calculations were performed for three days since the beginning of the waste water discharge.

The results obtained clearly demonstrate the presence of significant stratification in the formation of temperature fields (Fig. 2). Figures 2a and 2b show the temperature distribution fields. It can be seen that the greatest temperature impact on the water area is caused by the discharge of water from the outlet № 2, while water discharge from the outlet № 1 is cooled due to the inflow of cooler water through the culvert from the bottom horizon of the Magnitogorsk reservoir.

![Figure 2](image)

**Figure 2.** Temperature field (°C) in the surface layer of the Magnitogorsk reservoir (a), at a distance of 3 meters from the surface (b).

For elaboration of specific technical solutions, as well as recommendations of how to improve the operational efficiency of the structure under development, it was necessary to determine the horizon of the transition layer. To this end, 6 vertical reference lines were drawn on the water area and diagrams of the depth-wise water temperature distribution were constructed (Figure 3).

It should be noted that, depending on the location of the water outlets, the surge layer is located, on average, at a depth of 2-4 m. This is an additional substantiation of the fact that deeper (colder) water masses are poorly involved in the cooling process. This finding paves the way to studying possible measures of improving the efficiency of reservoir-coolers, over a relatively short period of maximum air temperature.

5. Conclusion

In this work, a numerical simulation of the distribution of thermal pollution in water bodies was carried out using as an example the water cooling system of the Magnitogorsk Metallurgical Plant. The discharge channel of this plant drains warm water in the Magnitogorsk reservoir of the Ural River.
The study was conducted for extreme technological and hydrometeorological conditions. The results of numerical computation revealed significant temperature stratification, the presence of which should be taken into account when designing new technological water intake structures. Water intakes should have such structures as to prevent water from flowing at a depth of 4 meters from the surface, because water at a given depth cannot be used in a direct-flow cooling process.

![Diagram of water temperature stratification](image)

**Figure 3.** Depth-wise distributions of water temperature at control points 1-6.

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