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Numerical modelling of the discharged heat water effect from thermal power plant on the aquatic environment

A. Issakhov

Department of Mathematical and Computer Modelling,
Faculty of Mechanics and Mathematics, al-Farabi Kazakh National University,
av. al-Farabi 71, 050040, Almaty, Kazakhstan, alibek.issakhov@gmail.com

Abstract — This paper presents a numerical modelling of the thermal discharge on the aquatic environment under various operational capacities of TPP, which is solved by the equations of Navier - Stokes and temperature for an incompressible fluid in a stratified medium based on the method of splitting by physical parameters that can be discretize by the control volume method. In the first step intermediate velocity field is solved by 5-step Runge - Kutta method. At the second stage Poisson equation for the pressure field is solved by Jacobi method. Finally at the third step is assumed that the transfer is carried out only by pressure gradient. The fourth step of the temperature equation is also solved as motion equations. The obtained numerical results of three-dimensional stratified turbulent flow reveals qualitatively and quantitatively approximate the basic laws of hydrothermal processes occurring in the aquatic environment.

1. Introduction

Environment - the basis of human life, and the energy generated - is the basis of the modern world. However, the production of electricity adversely impact on our environment, worsening living conditions. Energy is the basis of different types of power plants. Electricity production in thermal power plants (TPP), hydropower plants (HPP) and nuclear power plants (NPP) is associated with adverse effects on the environment. Interaction energy and the environment has acquired new features, extending the influence of heat on the rivers and lakes. With the increasing use of coastal waters for the economic and social needs of the growing sources and vulnerability of coastal waters due to the harmful effects of excess concentration of natural substances. Pollution associated with the release of industrial products, etc. require special attention and management of coastal waters. Chemical plants and power plants use the coastal water in large quantities for cooling and throw away the water in the environment with higher temperature. In the paper Suryaman et al. [33] modeled circulation system of cold water from thermal power plant Kilakap which was built and has being operating since 2006, which uses the water of the Indian Ocean as a cooling unit. Water passing through the condenser, is poured back into the ocean through the drainage system. Above the temperature of the water in the ocean is poured from thermal power plant the temperature of the water. It is important that poured warm water with drainage circulating did not get back into the water absorbent water cooling system, since otherwise the temperature water absorbent will continue to grow, in turn causing a temperature increase drainage, etc. temperature rise water absorbent and drainage. Any rise in temperature water absorbent reduces cooling efficiency (capacitors), which eventually leads to a decrease in overall plant efficiency. The heated water interacts with the natural conditions of the sea or rivers, affecting aquatic life. When the heat acts as a contaminant this called thermal pollutant. The temperature rise affects various physical and chemical properties of sea water such as density, viscosity, dissolved oxygen, salinity, turbidity, aquatic. Physical and chemical properties change directly affects the lives of marine organisms. Some sea creatures can counteract a rise in temperature, but not all organisms possible. The volume effect of the thermal water depends on the volume and temperature of water and poured seawater temperatures (near the drain), circulation flow around the drain. Heat transfer in coastal waters is part of the physical properties that depend on the tides, water depth, sea waves, river flows, salinity, heat source, coastal structures. In this paper Ali et al. [35] built interconnected numerical model, which is a three-dimensional temperature distribution of hot water thrown to standing water. This model is the relationship with the natural experiment, which was carried out on one side of one of the British Channel, using thermal cameras, as a source of shallow and stagnant water, and artificial experiment 10 times smaller, which was held in the laboratory. All three results give a good agreement. This model is used for calculating the temperature distribution in the channel when using water as a coolant channel for environmental purposes instead use conventional capacitors. After use water as the coolant water is returned again into the channel as a hot thermal dome discharged from the tube end. The model shows the heat-proportioned profile of the jet, which resets the thermal plume discharging horizontally into shallow and still receiving water. In the paper Beckers et al. [34] used a mathematical model and numerical simulation to verify operation of the circuit water circulation and thermal circulation imposed by the developer of energy-station seaport Zeebrugge in Belgium, on the North Sea coast. Particular attention was paid to the water cooling, as the classical method of cooling the released warm water in the main river was impossible because the internal port (harbor) Zeebrugge, which actually was planned station is not supplied with water from the river. This inner reservoir filled with sea water is cut off from the outer harbor and the sea with two gateways (barriers). The cooling system was the following power-station was planned in the inner harbor of Zeebrugge in Belgium with indirect emissions into the North Sea. If there is a stratification, the lower part of the water is colder, and surface water interact with the environment may lose some of the heat is also part of the surface water enters the main harbor of Zeebrugge through the channel. It is shown that the stratification is created in inland waters. In the main harbor evacuation of heat is mainly due to evaporation and only 20% due to the release of the open sea. Under different atmospheric conditions and operating conditions of the plant have been carried out work to determine the increase in temperature in the harbor and at the entrance to energy plant. The expected increase in the inlet temperature of the plant was expected 1.6^0C and 6.6^0C, but substantially increase in temperature is between $3-4^0C$. It was found that the main influence on the circulation of the internal reservoir is atmospheric conditions. But in the case of atmospheric conditions on the coast of Belgium, the temperature rise is not hard and not serious.

2. Background

The development of local circulation is directly dependent not only on the thermal contrast of the water surface and land. But also significant role is played by local orographic conditions. Probability of breezes' formation on the shores of large bodies of water depends on their geographical location. Changes in the wind direction at the reservoirs and on shore are connected not only with the local circulation. Differences in the roughness of the water surface and land lead to a rotation of the movement direction of the air mass to the right. When the air reaches especially high shore, it tends to move along it, because roughness of the land bigger than water. This gives the winds' rose the form of coastline. This effect is observed particularly clearly in narrow bays, at narrows of valley type reservoirs. One of the most effective methods of hydrodynamics study of the lake is a method of mathematical modeling. In some cases this may be the only tool to predict changes in the hydrological regime and lake ecosystems. For example, when studying the changes that may occur in spatial redistribution of water, while constructing waterworks and other events associated with the use of water objects. Mathematical models can be classified according to several criteria. It can be classified according to their model ”dimension” [12]: one-dimensional (vertical or horizontal), two-dimensional (horizontal or vertical plane), three-dimensional model. The most simple - are one-dimensional models that commonly used for modeling of currents in rivers. Two-dimensional models are used to study wind and seiche flows, storm surges, etc. Lick [25] proposes to consider the following types of mathematical models of wind currents like: 1) integrated model (full flow), in which vertical integration over the flow is accounted but vertical profile of flows not modeled, 2) stationary models of wind currents for constant and variable density of water 3) non-stationary model for barotropic and baroclinic lakes. To study the wind currents Sheng et al. [26] divided the models to: Ekman, integrated by vertical direction, multi-level and multi-layered. In addition to these models the dynamic method and a variety of three-dimensional thermohydrodynamic models are used for calculation of lakes' flows. Previously the impact of thermal discharged water from power plant to reservoir-cooler were studied by [13-15, 17, 18]. There are many mathematical and numerical models have been developed to simulate distribution of temperature from power plant to reservoir - cooler. In recent years, some advanced numerical models [19-24] have been developed for coastal oceans and estuaries with improved performance. These models have been used to simulate circulation and transport process.

3. Reservoir-coolers

Reservoir-cooler is divided into the following groups by appointment, location and conditions of supply:
regulating reservoir on the waterways used not only for cooling circulating water, but also for seasonal or long-term regulation of the flow;
reservoir-cooler in watercourses without flow regulation, under construction just to create a surface sufficient to cool the circulating water;
reservoir-cooler on natural lakes and ponds;
filling reservoir constructed out of watercourse fed from nearby rivers.

The free surface of the reservoir-cooler not totally equal effectively involved in giving the heat coming from the hot water circulation. The amount of heat withdrawn per unit area of a portion of the reservoir surface depends on the water temperature in this region. Therefore, a picture of the temperature distribution on the surface for calculation of the thermal process in reservoir-cooler is necessary to be presented. Consequently, it is necessary to chart the warm water flow distribution from its point of discharge with the place of its intake. Circulation scheme in the reservoir-cooler is determined by its shape, the mutual arrangement of the discharge and intake constructions and by jet distribution and jet guide's facilities. Considering the modern powerful power plants the design of large reservoir-cooler with depths reaching tens meters, and with the volume of water in the hundreds millions of cubic meters we should be aware that in addition to the gradient flows caused by discharge of the circulating flow and intake of river water in reservoirs, there are also wind, density and compensation flow. Wind currents cause the water ebbs from the leeward side of the pond and surges it at the windward side. This occurs when the horizontal pressure gradient directed in the direction opposite to the wind, it is a type of deep compensating flows. It is known that water has the highest density at 4^0C, but when heated its density decreases. The heat transfer into the water column due to molecular diffusion and thermal conductivity is very weak. Therefore, water temperature stratification is occurred by heating of the upper layers: the surface of water temperature is higher than in the deep layers, and this difference sometimes reaches 10^0C or more. Water temperature difference in the upper and lower layers may become stable with the discharged warm water to the surface of the reservoir. Hence, it leads to a bundle of threads having different density. This case raises the upper warm and deep cold flows, which can be multi-directional.

4. Mathematical modelling

In reservoir - coolers spatial temperature change is small (it usually does not exceed 20^0C). Corresponding change in the density is much smaller than the magnitude of the water density. Therefore, stratified flow in the reservoir - cooler can be described by the equations in the Boussinesq approximation, i.e. in the motion equations a variable of water density can be replaced by some constant everywhere except the members representing the Archimedean force. In view of the above, the starting point for describing the flow in the laminar regime is the Navier - Stokes equation and transport equation for temperature [1, 2, 3, 13-15, 31]. Compared to papers [13-15] in this work and in papers [1, 2, 3] stratification development is taken into account, which is added to the right hand side of motion equation and have the following form:

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}\right) + \delta_{i3}\beta g(T - T_0) \tag{1}$$

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{2}$$

$$\frac{\partial T}{\partial t} + \frac{\partial u_j T}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\chi \frac{\partial T}{\partial x_j}\right) \tag{3}$$

where g the gravitational acceleration, β coefficient of volume expansion, u_i - velocity components, χ the thermal diffusivity, T_0- the equilibrium temperature, $T-$ the temperature deviation from equilibrium.

The system of equations are written in the Cartesian coordinate system in the physical space $x_i(i = 1, 2, 3)$, the three components of velocity u_i and pressure p are unknown functions, t - time, ν - the kinematic viscosity of the medium (molecular). Repeated indices should be the summarized in the system of equations (1) - (3) and below.

In the general case, the system of equations (1) - (3) in such way can not be solved because a turbulent model needs to be applied. Large eddy simulation method [4, 28] is used as the turbulent model. Averaged by Favre [4, 6, 7, 10] the system of equations (1) - (3).

This system of equations can be closed by Smagorinsky model [4, 16]. But in this study a dynamic model of Smagorinsky [3, 4, 6, 9] is used as a model of turbulence.

The finite volume method [6, 7] is used for the numerical simulation. We represent the Navier - Stokes equation and transport equation for temperature in the integral conservation laws form for arbitrary fixed volume $\Omega$with the boundary $d\Omega$ [6, 7, 8]:

$$\int_\Omega \left(\frac{\partial U}{\partial t} + \frac{\partial F_i}{\partial x_i} + \frac{\partial G_i}{\partial x_i} - B_i\right) d\Omega = 0, \tag{4}$$

where

$$U = \begin{pmatrix} 0 \\ u_j \\ T \end{pmatrix}, \quad F_i = \begin{pmatrix} u_i \\ u_i u_j + p\delta_{ij} - \tau_{ij} \\ v_i T \end{pmatrix}, \quad G_i = \begin{pmatrix} 0 \\ \nu \frac{\partial u_i}{\partial x_j} \\ \chi \frac{\partial T}{\partial x_j} \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ \beta g_i (T - T_0) \\ 0 \end{pmatrix}.$$

Now we perform a discretization of equation (4) in the control volume (CV) and the control surface (CS)

$$\sum_{CV}(\frac{\Delta U}{\Delta t})\Delta\Omega + \sum_{CS}(F_i + G_i)n_i\Delta\Gamma = \overline{B_i}\Delta\Omega \tag{5}$$

5. Numerical algorithm

A good description of the topographic contours of the Zhyngyldy reservoir-cooler shore is required for hydrodynamic modeling. Splitting scheme by the physical parameters is used to solve Navier - Stokes equation and transport equation for temperature, which was proposed by Chorin [11] and used in [5, 8]. Discretization in form of (5) is used for the numerical implementation of the system of equations. At the first step it is assumed that the momentum transfer carried out only by convection and diffusion. Intermediate velocity field is solved by is 5-step Runge - Kutta method [29, 30, 32]. At the second stage, the found intermediate velocity field, forms pressure field. Poisson equation for the pressure field is solved by Jacobi method [6]. The third step assumes that the transfer is carried out only by pressure gradient [5, 11]. The temperature field is solved like the velocity field by 5-step Runge - Kutta method. The numerical algorithm is parallelized on high-performance system and a block partitioning computational domain is used for parallelization algorithm. Below we can see mathematical expressions of numerical algorithm for four stages (splitting scheme by the physical parameters):

I) $\int_\Omega \frac{\vec{u}^* - \vec{u}^n}{\tau} d\Omega = -\oint_{\partial\Omega} (\nabla(\vec{u}^n\,\vec{u}^* - \tau_{ij}) - \nu\Delta\vec{u}^* + \delta_{i3}\beta g(T - T_0))n_i d\Gamma,$

II) $\oint_{\partial\Omega} (\Delta p) d\Gamma = \int_\Omega \frac{\nabla\vec{u}^*}{\tau} d\Omega,$

III) $\frac{\vec{u}^{n+1} - \vec{u}^*}{\tau} = -\nabla p,$

IV) $\int_\Omega \frac{T^* - T^n}{\tau} d\Omega = -\oint_{\partial\Omega} (\nabla\vec{u}^n\,T^* - \chi\Delta T^*)n_i d\Gamma.$

6. The results of numerical simulation

To study the vertical inhomogeneities in stratified reservoirs mathematical model was selected and numerical algorithm was developed, which was taken from satellite data. It is necessary to do numerical simulations and to compare the results with experimental data in order to check the correctness of the numerical algorithm and the possibility of their further application. Note that we have data only by the vertical distribution of temperature of Ekibastuz SDPP-1 Zhyngyldy Lake. However, these measurements were carried out in 2010 and for the operational capacity of 200 MW. So the verification of the models was carried out on these experimental data. In [27] it is noted that, despite the different weather conditions in different years, the vertical thermal structure of the water does not undergo changes cardinally. Therefore, at the first phase, a mathematical model was validated by experimental data measured in 2010. The results were compared with experimental data. The results of numerical simulations of the temperature distribution along the depth of the reservoir and the experimental data for the operational capacity of 200 MW for different points on reservoir-cooler, which are presented in figure 1, are shown below in figures 2 - 3. The calculated spatial contour and the isolines of the temperature distribution at different times after the start of Ekibastuz SDPP-1 on the surface of water for the operational capacity 200 MW is shown on the figure 4. Figure 4 shows that the temperature distribution with distance from the discharge is approaching an isothermal condition. These results

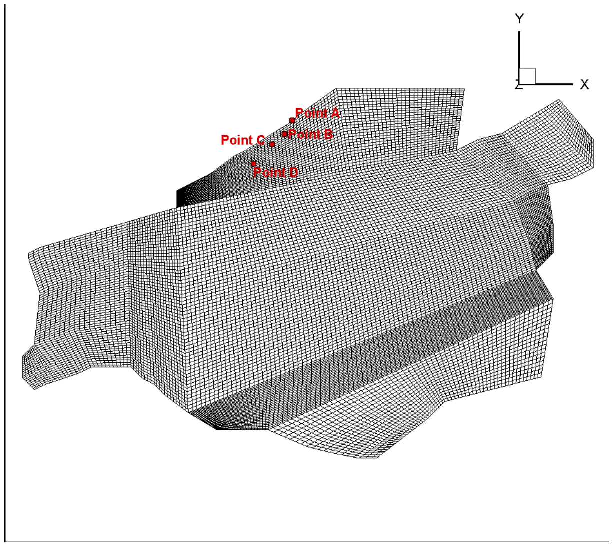

Figure 1: Computational grid for Ekibastuz SDPP-1

show that the temperature distribution is spread over a large area of reservoir-cooler. And also from the same figure it can be seen that an increase of thermal power plant's operational capacity, the area of thermal effect becomes directed in the same way, and leads to water warming of only one part of the reservoir, which has a negative effect on the performance of TPP. It to an increase in the operational capacity of Ekibastuz SDPP-1 of reservoir-cooler is not effective, fueling the western part of the reservoir, and the rest is not involved in cooling of heated water from thermal power plant that is resulted in the rapid warming of reservoir-cooler.

Thus, the advanced three-dimensional model of a stratified turbulent flow reveals qualitatively and approximately quantitatively the basic laws of hydrothermal processes in the aquatic environment.

Figures 2-3 of the drawings shows that the numerical results agree with the experimental data. A difference in the upper layers can be explained by variations in weather conditions at various times of the day. And also from the figures 2-3 it can be seen that the calculated data from models show quite good results for the operational capacity 200 MW. The calculated spatial contour and the isolines of the temperature distribution at different times after the start of Ekibastuz SDPP-1 on the surface of water for the operational capacities 200 MW, 800 MW are shown on the figures 4-5 respectively. Figures 4 - 5 show that the temperature distribution with distance from the discharge is approaching an isothermal condition. These results show that the temperature distribution is spread over a large area of the reservoir-cooler. Models allow us to determine the qualitative vertical structure, the position of the transition zone for the temperature values at the lower and upper layers. Note that mixing occurs under the influence of turbulence and mixing have a significant effect on the flow. The fact that the results are in good agreement with the experimental data says that an adequate simulation of the wind currents. The picture of the wind currents depends on the strength of the wind, stratification and reservoir geometry. A series of calculations were carried out, resulting in the obtained data on the nature of flows, which can be illustrated by some specific examples. One circulation zone is formed for a homogeneous fluid in the reservoir. Furthermore with the increase in the length of the reservoir increases the maximum speed of the water flow.

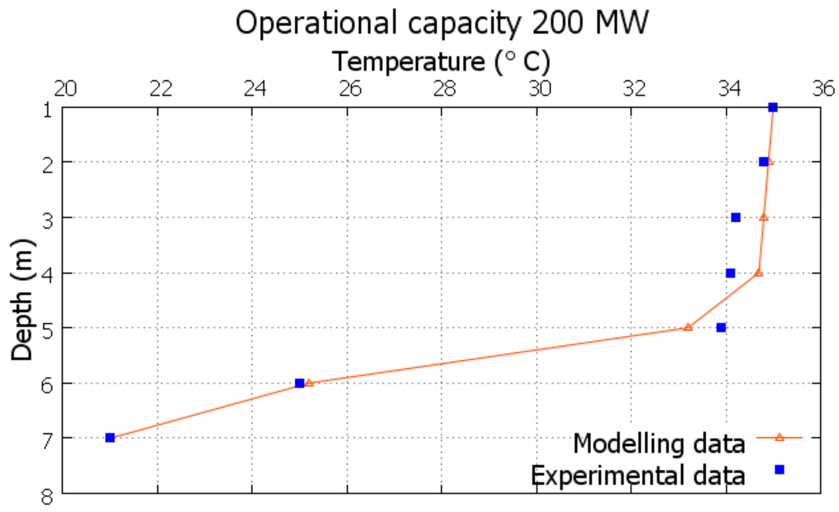

Figure 2: Comparison of experimental data with simulation data for the operational capacity 200 MW at the point A.

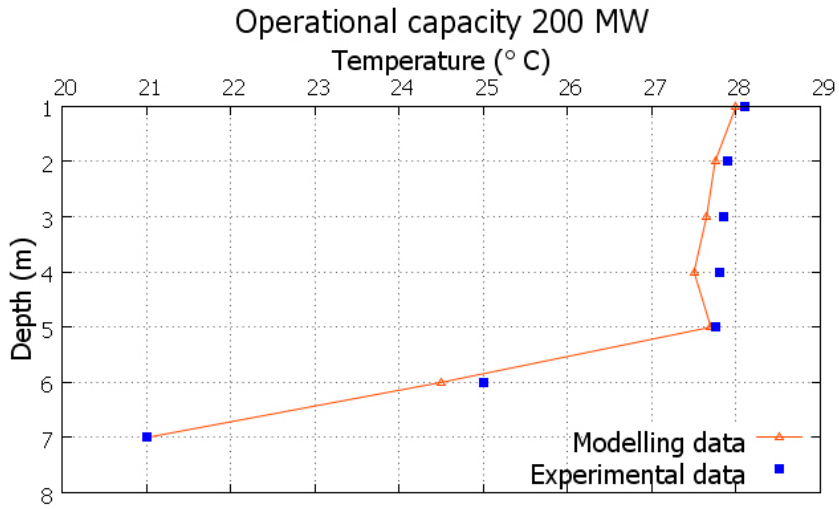

Figure 3: Comparison of experimental data with simulation data for the operational capacity 200 MW at the point B.

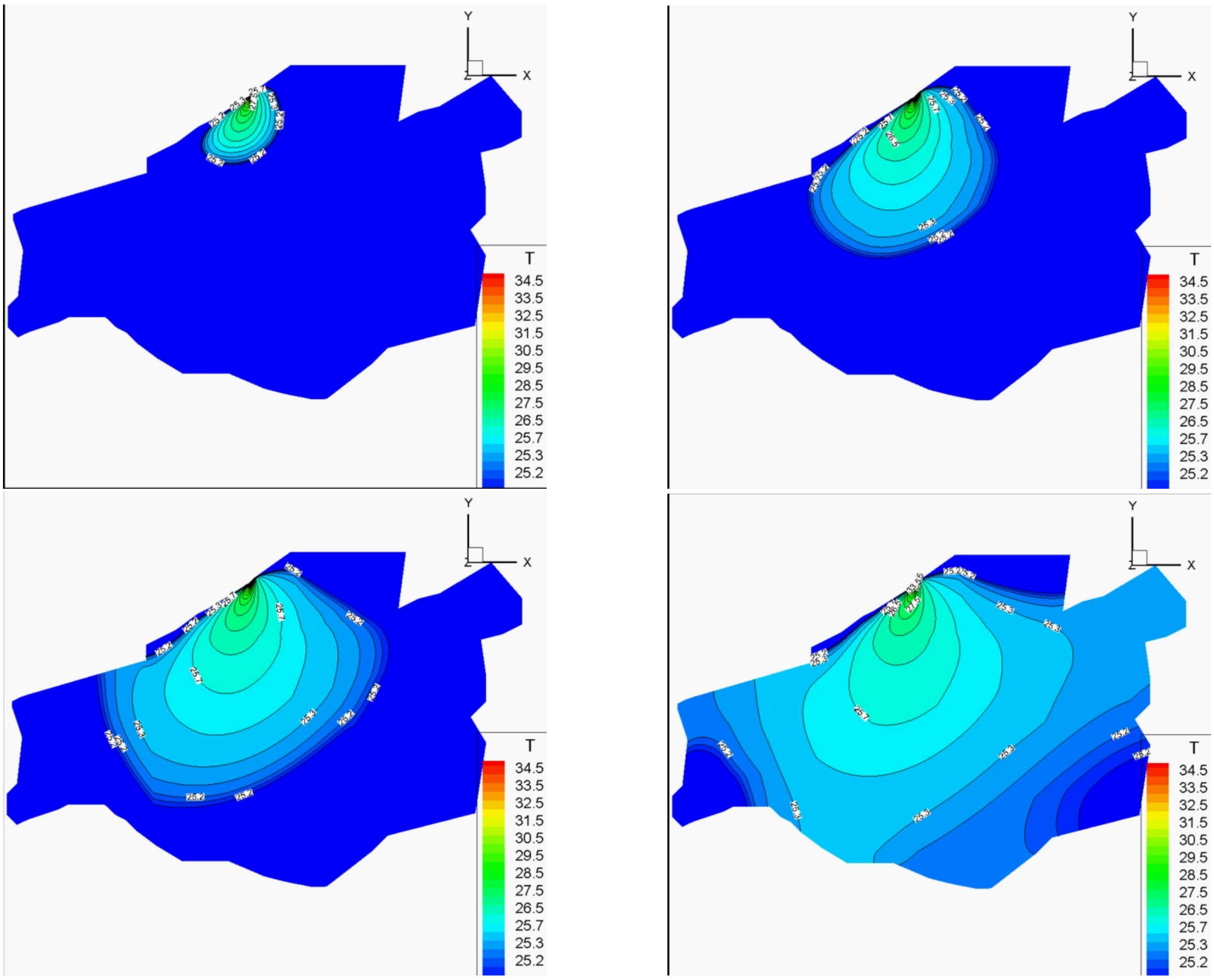

Figure 4: The spatial contour and isolines of the temperature distribution at 1, 5, 12 and 24 h. after the start of Ekibastuz SDPP-1 on the surface of water for the operational capacity 200 MW.

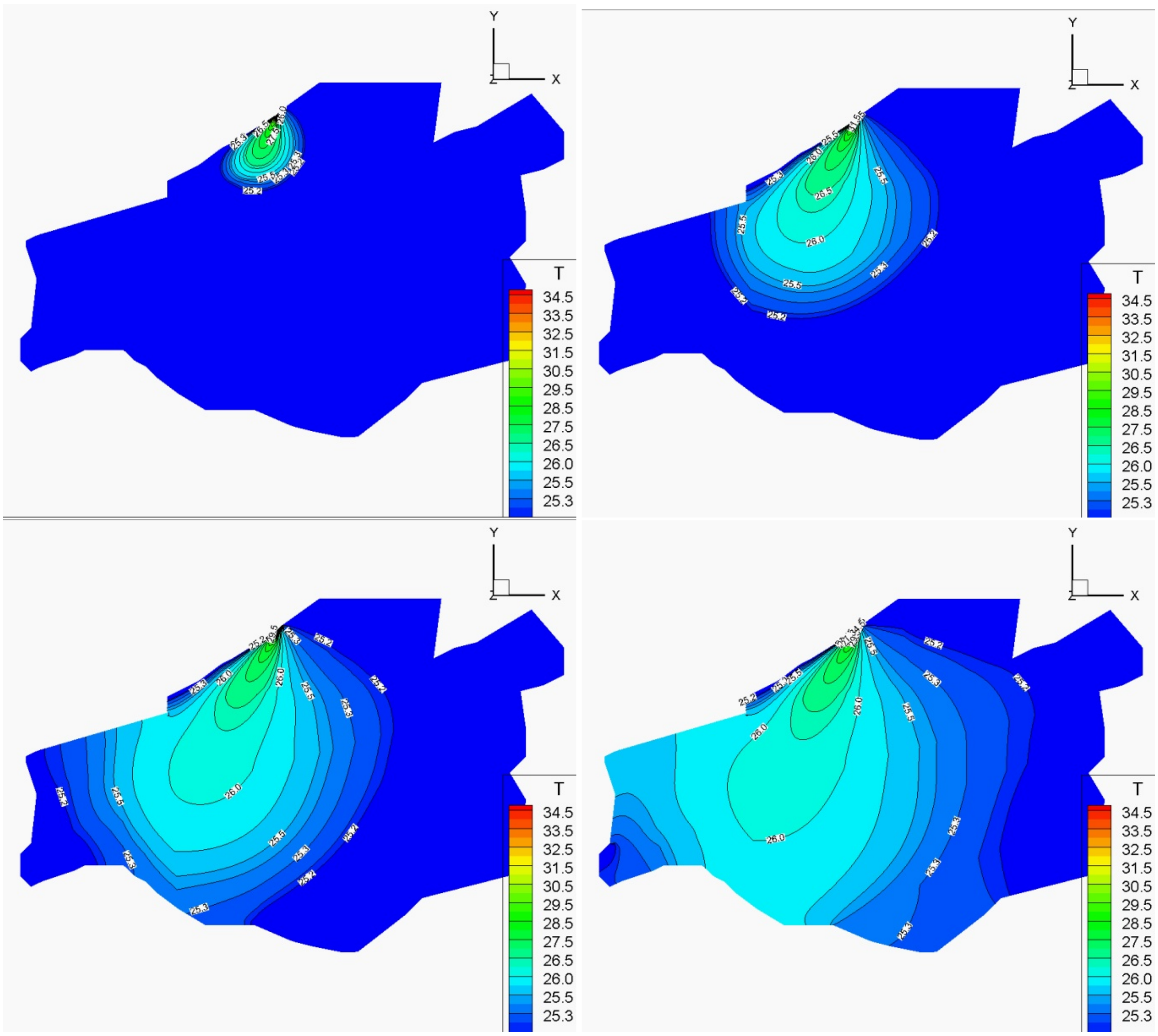

Figure 5: The spatial contour and isolines of the temperature distribution at 1, 5, 12 and 24 h. after the start of Ekibastuz SDPP-1 on the surface of water for the operational capacity 800 MW.

7. Discussions

LES is a more universal approach to close the system of equations which was filtered by Favre approach. A necessary condition for the performance of turbulent closures are ”subgrid” model that correctly describes the dissipation of the kinetic energy of smoothed velocity fluctuations and the ability to simulate the circuit direct energy cascade from large to small eddies. This stage is the primary mechanism for the redistribution of energy in the inertial range of three dimensional homogeneous isotropic turbulence. The principal advantage of the LES from RANS is that, due to the relative homogeneity and isotropy of the small-scale turbulence, plotting a subgrid model is much simpler than the use turbulence models for RANS, when it is necessary to model the full range of turbulence. For the same reason, the hope for a ”universal” subgrid model for LES is much more reasonable than a similar model for RANS. These important benefits of LES increase significantly computational cost associated with the need (also for Direct numerical simulation (DNS) case) of three-dimensional time-dependent calculations on sufficiently fine grids. Even also in cases where direct interest to the practice of the average flow is two-dimensional and stationary. On the other hand, for obvious reasons, the computational resources which are required to implement the LES, are much smaller than for the DNS. The degree of influence of different processes governing the formation of stratified flows and hydrothermal conditions in the entire body of water can be divided into two zones. The first (near) zone, directly adjacent to the water of outlet structures. The second is for the major part of the reservoir. In the near zone formation of the stratified flow is influenced by the processes of mixing discharged water with water from the reservoir. It should be regulated by creating a specific hydraulic regime in the outfalls. In the second zone of hydrothermal regime is formed primarily by the processes of heat transfer. The propagation of heat in this part of the reservoir is more dependent on the wind (direction and speed). When you spread the heated water in a cold environment density difference between the upper layer of warm water and bottom layer of cold water appears. This allows the use of a combined intake and discharge instead of building costly diversion canals to the discharge. Accordingly raises the problem of optimal choice of the geometrical and operational parameters of the reservoir - cooler for efficient work of power plant.

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