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Mathematical modeling of the thermal discharge under various operational capacities of thermal power plants

Abstract. This paper presents a mathematical model of the thermal discharge under various operational capacities of thermal power plants, 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 it is assumed that the transfer of momentum carried out only by convection and diffusion. Intermediate velocity field is solved by 5-step Runge - Kutta method. At the second stage, the pressure field is solved based on the found intermediate velocity field. The algorithm is parallelized on high-performance systems. The obtained numerical results of three-dimensional stratified turbulent flow reveals to approximate qualitatively and quantitatively the basic laws of hydrothermal processes occurring in the aquatic environment.
Keywords: stratified medium, Navier-Stokes equations, operational capacity of TPP, finite volume me-thod, Runge-Kutta method.

Introduction

It is known that the environment - the basis of human life, and the energy generated from resources is the foundation of the modern world. However, production of electricity adversely impact to the environment, worsening living conditions. Actually the bases of energy are different types of power plants. Electricity that was produced by thermal power plants (TPP), by hydropower plant (HPP) and by nuclear power plants (NPP) associates with adverse effects on the environment. The interaction of energy and the environment as a result give us that extends the influence of heat on the rivers and lakes.

Previously, the impact of TPP or NPP on the environmental was not taken into account, since the main purpose was to obtain electricity. Technology of electricity production from the power plant is connected with a lot of heat emission into the environment. Negative impact of energy on the environment is becoming an important issue, since pollution increasing year by year.

Today it is important to find the best sources of electricity. The TPP is the alternative. In TPP burn fuels, i.e. coal, gas or oil. The generated heat converts water into steam, which drives turbines and then generators. Water vapor is cooled and again converted into water, and heated again and etc. In small TPP additionally so-called fossil fuels, i.e. coal, natural gas or oil, you can also use other fuels, such as straw or fast-growing trees.

TPP is divided into condensing (CPP), that is intended only to generate electricity and thermal power central (TPC), which besides producing electricity gives us additional heat in the form of hot water or vapor. Large CPP with regional value is called state district power plants (SDPP).

Electricity generation in thermal power plants occurs through sequential stages. Initially, fuel is burned (coal, gas, etc.) in the vapor boiler, wherein released the heat, which converts water into vapor. Continuing incoming vapor pressure rotates turbine rotor, which transmits rotational energy to the generator shaft, and in the result produced electrical current. The vapor after passing through the turbine is condensed into the water again, which further passes through the heater and re-enters the vapor boiler.

All power plants adversely affect to the environment. TPP impact on the aquatic environment is manifested in such highlights: plum of liquid pollutants into water bodies; deposition of solid particles on the water body surfaces when happens the particulate emissions of these particles into the atmosphere; thermal pollution of reservoirs, etc.

The water is used in TPP for cooling condensers devices of steam turbines, water-, air-, etc. coolers, which is taken from ponds or rivers. Large amount of thermal emission is made into reservoirs or rivers by taking heated water. About 2/3 of the total amount of produced heat by the combustion of coal, oil, etc. is assigned to the turbine condensers. Therefore condensers cooling is associated with thermal pollution of reservoirs or rivers because of discharged water from TPP. Amount of heat withdrawn from the cooling water of thermal power plants can be identified by installed capacity of power plant. Hot water is cooled in a cooling tower, and then heated water is discharged into a reservoir or river. As a result heated water is discharged into reservoir or river, which adversely affects the aquatic environment, and reduces the concentration of oxygen, also promotes the rapid growth of algae, and the extinction of aquatic flora and fauna. It is also necessary to say that the waste of heat leads to a change of microclimate of reservoir or river. Thus, the water evaporates from the cooling tower, raises the ambient of air humidity, which leads to the formation of fog and clouds.

TPP with cooling water shed 4 - 7 kJ of heat for 1 kW/h of generated electricity. But Health Standards discharges that warm water from TPP should not raise the temperature of the reservoir higher than $3^0 C$ in summer and $5^0 C$ in winter.

Propagation of thermal emissions from thermal power plants depends on several factors: the terrain, ambient temperature, wind speed, cloud cover, residues, etc. Moreover it accelerates the spread and increases the area of thermal pollution hydrometeorological conditions.

Both thermal and nuclear power plants require in reservoirs. Large amounts of water for cooling units is required to operate these stations, averagely of 35-40 $m^3/\sec$ to 1 million kW of installed capacity. Hence, it becomes obvious that 70-160 $m^3/\sec$ of water is required for thermal power plants of 2.4 million kW. Therefore, the water supply is an important issue for building thermal and nuclear power plants. Naturally, the large thermal power plants should be located on the banks of large rivers, reservoirs and lakes or artificial reservoirs.

Ekibastuz- 1, located in the Pavlodar region 17 km. northeast of Ekibastuz city, Kazakhstan is taken as an example of thermal effects to the aquatic environment from TPP.

Mathematical model

In reservoir-cooler spatial variation of temperature is small. Therefore, stratified flow in the reservoir-cooler can be described by the equations in the Boussinesq approximation. For mathematical modeling of the system of equations are considered, which including the equations of motion, the continuity equation and the equation for the temperature. The development of three-dimensional turbulent flow in a stratified reservoir-cooler is considered. Three-dimensional mathematical model is used for modeling of temperature distribution in the reservoir [1,2,3]:

$$\frac{\partial \overline{u_i}}{\partial t}+\frac{\partial \overline{u_j u_i}}{\partial x_j}=-\frac{\partial \overline{p}}{\partial x_i}+\nu\frac{\partial}{\partial x_j}\left(\frac{\partial \overline{u_i}}{\partial x_j}\right)+\beta g_i(T-T_0)-\frac{\partial \tau_{ij}}{\partial x_j}, \quad (1)$$

$$\frac{\partial \overline{u_j}}{\partial x_j}=0, \quad (i=1,2,3), \quad (2)$$

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

where $\tau_{ij}=\overline{u_i u_j}-\overline{u_i}\,\overline{u_j}$, $g_i -$ gravitational acceleration, $\beta -$ expansion coefficient, u_i – velocity components, $\chi -$ thermal diffusivity, $T_0 -$ equilibrium temperature, $T -$ temperature deviation from equilibrium.

Smagorinsky turbulence model is used to close the system of equations (1) - (3) [4].

The finite volume method is used for the numerical simulation. For this purpose let us represent the Navier-Stokes equation and equation for the temperature in the form of integral conservation laws for arbitrary fixed volume Ω with boundary $d\Omega$ [6,7,8,9,10]:

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

where

$$U = \begin{pmatrix} 0 \\ u_j \\ T \end{pmatrix}, \quad F_i = \begin{pmatrix} u_i \\ u_i u_j + p\delta_{ij} - \tau_{ij} \\ v_i T \end{pmatrix},$$

$$G_i = \begin{pmatrix} 0 \\ \nu \dfrac{\partial u_i}{\partial x_j} \\ \chi \dfrac{\partial T}{\partial x_j} \end{pmatrix}, \quad B = \begin{pmatrix} 0 \\ \beta g_i (T - T_0) \\ 0 \end{pmatrix}.$$

equation (4) can be written in this form

$$\int_\Omega \left(\frac{\partial U}{\partial t} - B \right) d\Omega + \oint_{\partial\Omega} (F_i + G_i) n_i d\Gamma = 0. \quad (5)$$

And we can write the equations (5) like

$$\int_\Omega \left(\frac{\partial U}{\partial t} \right) d\Omega + \oint_{\partial\Omega} (F_i + G_i) n_i d\Gamma = \int_\Omega B_i d\Omega. \quad (6)$$

Grid functions are defined at the cell center, and fluxes across the border in divided cells. Cell volume is denoted by the grid functions.

Now we perform a discretization of equation (6) by the control volume (CV) and control surface (CS)

$$\sum_{CV} \left(\frac{\Delta U}{\Delta t} \right) \Delta\Omega + \sum_{CS} (F_i + G_i) n_i \Delta\Gamma = \overline{B_i} \Delta\Omega \quad (7)$$

or we can write the equation (7) in this form:

$$\sum_{CV} \Delta U \Delta\Omega + \sum_{CS} \Delta t (F_i + G_i) n_i \Delta\Gamma = \Delta t \overline{B_i} \Delta\Omega. \quad (8)$$

Numerical algorithm

Splitting method by physical parameters is used to solve the equation (1) – (3) [5,6,7]. Discretization in form of (8) is used for the numerical implementation of the system (1) – (3). In the first step it is assumed that the transfer of momentum carried only by convection and diffusion. The intermediate velocity field is solved by 5-step Runge - Kutta method. In the second stage, the pressure field is found based on the found intermediate velocity field. Poisson equation for the pressure field is solved by Jacobi method. The third step it is assumed that only the transfer is carried out by pressure gradient. The algorithm is parallelized on high-performance systems. Simulations were made on cluster systems URSA and Cluster of Institute of Mathematics and Mechanics at the al-Farabi Kazakh National University. Finite volume method and a similar calculation like the equations of motion are also used by solving the equation for the temperature [11].

$$\text{I)} \quad \int_\Omega \frac{\vec{u}^* - \vec{u}^n}{\tau} d\Omega = -\oint_{\partial\Omega} \left(\nabla \vec{u}^n \, \vec{u}^* - \nu \Delta \vec{u}^* \right) n_i d\Gamma,$$

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

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

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

Results of numerical simulation

Initial and boundary conditions were determined to solve the problems. More than 100 000 grid points were used in simulations. Figure 1 shows the computational grid for the SDPP- 1. Figure 2 shows the calculated spatial outline and contour of the temperature distribution at different times after the start of SDPP-1 on the surface of the water for the operational capacity of 800 MW. Figure 3 shows the spatial outline and the contour of the temperature distribution at different times after the start of SDPP-1 on the surface of the water for the operational capacity of 1200 MW. In both 2-3 figures it can be observed that the temperature distribution with distance from discharging point become to the isothermal state. These results show that the temperature distribution is spread over a larger area. As it can be seen from the figures 2-3, area of thermal effects becomes directed to one direction when the operational capacity of SDPP-1 increases. Subsequently it leads to water heating of only one part of the reservoir. As a result it has a negative effect on the performance of SDPP-1. When the operating power 1200 MW, the temperature is distributed in the western part of the reservoir and uses only approximately half of the reservoir. With increasing operating power of SDPP-1 reservoir-cooler does not work effectively. To be more precise warming the western part of the reservoir, while the rest is not involved for cooling the heated water from the power plant.

Thus, developed three-dimensional stratified turbulent flow model, qualitatively and quantitatively to approximate identifies the basic laws of hydrothermal processes occurring in the aquatic environment.

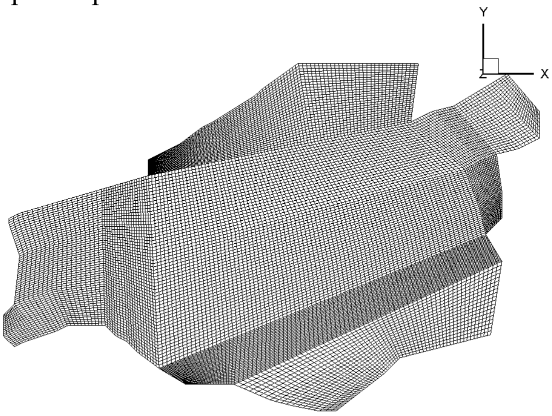

Figure 1 – Computational grid for SDPP-1.

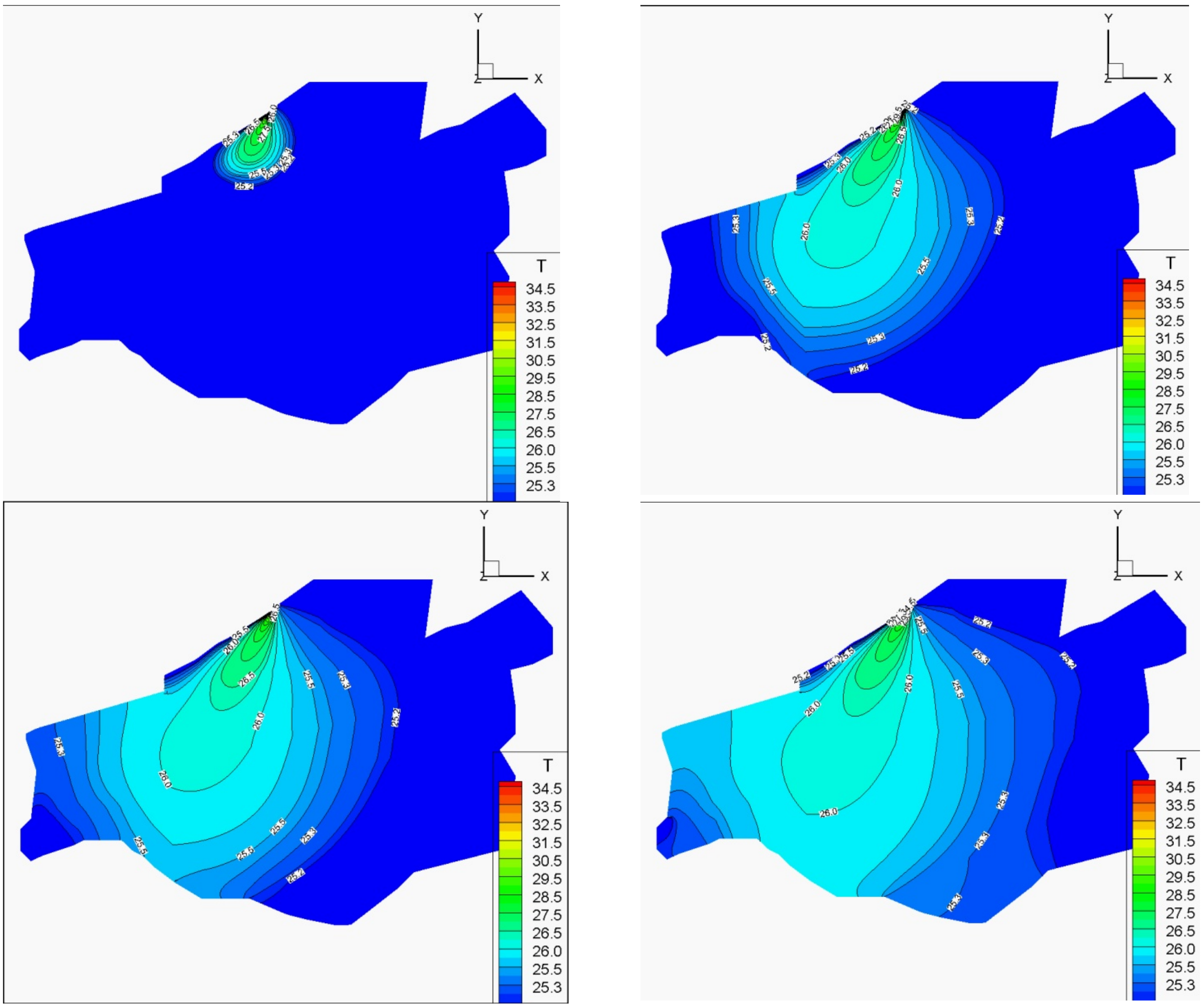

Figure 2 – Spatial outline and contour of the temperature distribution at 1, 5, 10 and 24 hours after the start of SDPP-1 on the surface of the water for the operational capacity of 800 MW.

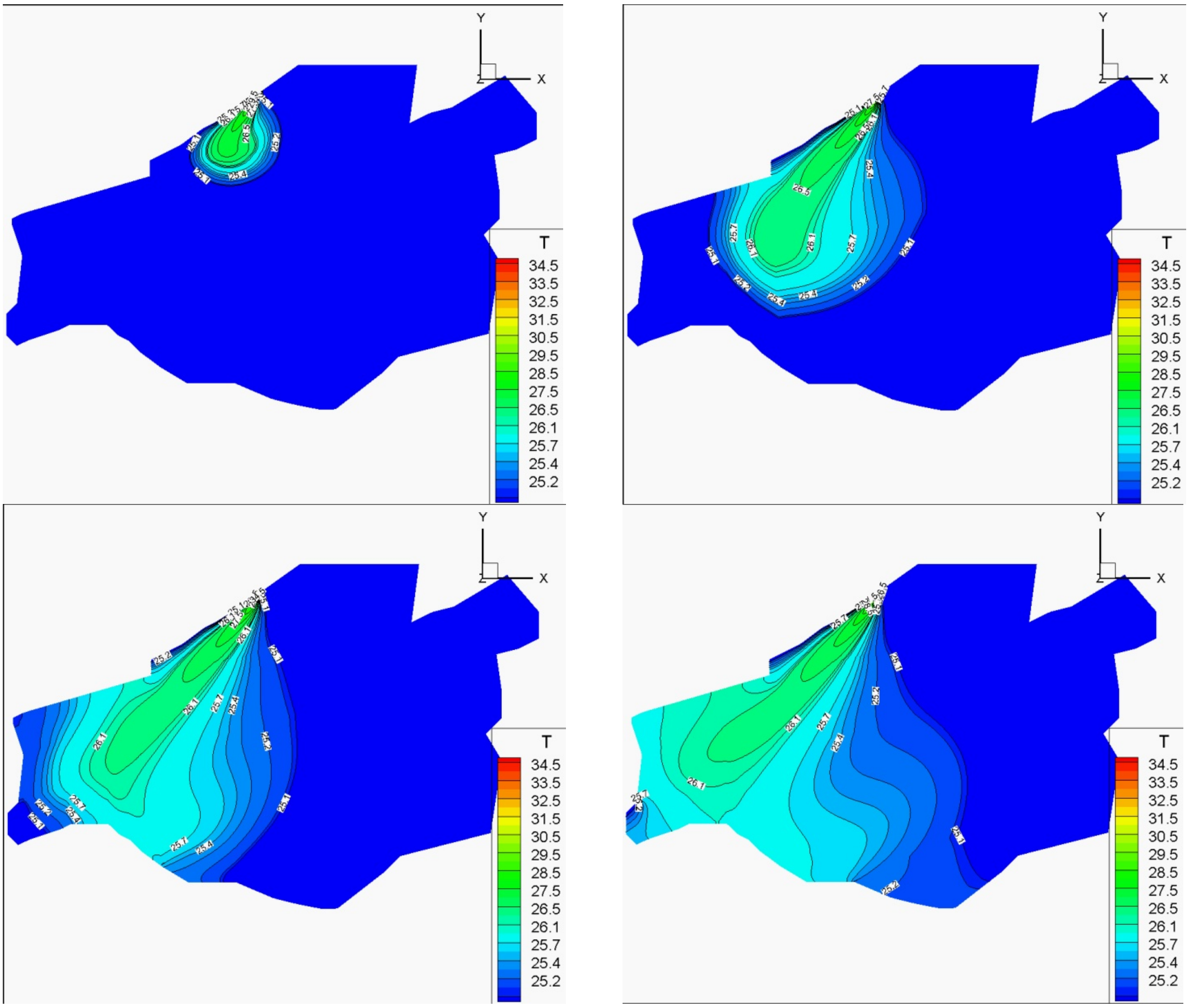

Figure 3 – Spatial outline and contour of the temperature distribution at 1, 5, 10 and 24 hours after the start of SDPP-1 on the surface of the water for the operational capacity of 1200 MW.

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