International Journal of Heat and Mass Transfer 126 (2018) 342–352

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The modeling of the formation of technogenic thermal pollution zones in large reservoirs

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ARTICLE INFO

Article history:
Received 5 March 2018
Received in revised form 23 April 2018
Accepted 3 May 2018

ABSTRACT

Thermal pollution of water bodies is an unavoidable consequence of thermal or nuclear power plant operation. To minimize the detrimental effects of these plants, one should assess the nature of dangerous zones. The most effective approach to solving these problems is the computational experiment. This paper presents the results of a numerical study of thermal pollution in one of the largest thermal power plants of Europe - Permskaya TPP, using the Kama Reservoir as a natural cooling system. Such problems are traditionally solved in 2D formulation using the "shallow water" approximation. However, with this approach it is impossible to take into account the vertical inhomogeneity of the temperature field. On the other hand, 3D models, which can take into account the effect of density stratification, require very large computational resources. In this work, a combined approach, based on a combination of computational models in the 1D, 2D and 3D formulations, is applied.

1. Introduction

Today, water basins are the most widely used types of cooling systems for large thermal and nuclear power plants. Their exploitation often involves considerable problems peculiar to a particular basin [1–3]. For small cooling basins the problems are associated with the operating limits of a power plant related to a rise of the temperature of water withdrawn from the reservoir [4], whereas for large cooling systems the problems are related to thermal pollution, changes in the ice-thermal regime, hydrophysical and hydrobiological processes, especially in the areas of discharging heated water [5,6]. A key to the solution of a variety of technological and ecological problems is getting the comprehensive and reliable estimates of the parameters of temperature fields generated by these discharges in relation to the technological and hydrometereological parameters [7,8]. The necessary condition for solving the problem of technological and environmental constraints associated with the detrimental impacts of power plants on water bodies is gaining complete and detailed information on the temperature fields in various meteorological and hydrological conditions.

The significance of the problem under consideration is determined by the fact that it came into the view of researchers in early 30-ies of the XX century giving impetus to the development of the first applied models of "plane" hydrodynamics. There are several reasons why finding solutions to these problems is a challenging task. Among the most important complicating factors are the fractality of morphometry of natural water bodies, considerable difference in the scales of natural and technological parameters, and essential variability of hydrometereological factors. Generally, as shown in [9], the coastline represents a fractal and therefore, even a significant refinement of the computational mesh does not give an equivalent increase in the efficiency of the approximation.

Earlier, the restricted efficiency of the computing facilities was one of the main limiting factors. The most widely used approach to these problems was 2D modeling based on the shallow water approximation (see, for example [10–14]). In [9], the authors describe the methods of computational hydrodynamics, which are based on 1- and 2-D modeling. The compact finite difference methods are described in [11]. In [12], a model of sea ice motion, taking into account the atmospheric and water flows due to temperature inhomogeneities, is constructed based on the data of temperature monitoring in the Arctic and Antarctic regions. A 2D-numerical simulation of the spread of thermal pollution in the coastal area of the Red Sea is performed in [13]. An effect of thermal pollution produced by the Iran thermal power plant is numerically investigated in [14] using the 2D approach. Consideration is given to different weather scenarios and temperatures.

However, numerous data of field observations generated the need for revising the formulation which is based on the

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.017
0017-9310/

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 [15–19], the problems of thermal pollution are solved in the framework of such models. Apukhtin et al. [15], the maximum temperature of water in the Beloyarsk reservoir (Russia) was computed using a in-house code, in which the equations of hydrodynamics in the hydrostatic approximation and the energy equation in the 3D approximation are solved by the finite difference method. In [16], a three-dimensional computational package of hydrodynamics (MIKE 3) is used to calculate the temperature field and flows in the East –River river (New-York)) generated under the influence of two thermal power plants (TPP). The computational grid composed of triangular elements was refined near the hot water discharge. An estimate of the maximum water discharge for the worst-case pollution scenario was obtained.

The importance of appropriate resolution of spatial models for correct estimation of the propagation of thermal pollution in rivers is discussed in [17]. In [18] the authors discuss the possibility of combining the models of one-dimensional (1D) and three-dimensional (3D) approximations for studying thermal pollution in lakes caused by a single source.

In works [19–21], a three dimensional numerical simulation of turbulent mixing of water layers of different temperatures was carried out based on the solution of the Navier-Stokes equations and LES approach. Computations were done using a three – stage scheme with parallelization. The computational aspects of the LES approach were discussed in [22–24].

The results of three-dimensional numerical simulation of thermal pollution spreading from the cross flow in the river are presented in paper [25]. The dependence of jet inclination on the depth of the main stream was investigated.

In this paper, with reference to the Permskaya thermal power plant, which is one of the most powerful thermal power plants in Europe, we investigated the temperature fields generated due to a discharge of heated waters taking into account the technological and hydrometeorological parameters.

2. Methodology

2.1. In-situ measurements

The Permskaya TPP is situated on the left bank of the Kama reservoir 5 km upstream from the city of Dobryanka and 60 km upstream of the Kamskaya hydropower plant (Kamskaya HPP) dam. Water is supplied from the Kama reservoir through the intake channel and is withdrawn back into reservoir through the discharged channel (Fig. 1). According to technical specifications, the capacity of the thermal power plant must be as large as 4800 thousand kilowatt (6 power generating units, each of 800 thousands kW). Three power units of total capacity of 2400 thousand kW equipped with a direct cooling system are currently in operation. The projected series of studies based on the computational experiments were aimed at minimizing the possible adverse environmental and technological impacts when choosing the optimal cooling schemes for the power units under development.

The Kama reservoir is morphologically a relatively shallow-water zone, in which the average depth does not exceed 4–7 m. Water from the reservoir is carried out through the water intake channel (2.3 km long) and is withdrawn into the reservoir through the discharge channel (900 m long). The width of the reservoir is about 4.0 km. The inundated bed of the Kama river runs along the opposite bank, where the maximum depth is as large as 23 m (Fig. 2).

The most important parameter for restricting water usage in the examined region of the reservoir is the maximum temperature in the area of operation of the Permskaya TPP. According to the Water Code of the Russian Federation, it is not permitted to increase the temperature of water in surface water bodies due to the thermal discharges by more than 5 °C, in comparison with the natural background temperature. Therefore, it is important to identify the zones with maximum temperature for the hottest period of the year. In this context, the procedure for evaluating the specific features of zones, which may experience thermal pollution during operation of the Permskaya TPP, was implemented in two steps. At the first stage the parameters of temperature fields generated by the discharge of heated TPP water were estimated based on the in-situ measurements and the schemes of model calculations were developed. The second-stage study concerned the verification of the computational models and the implementation of the developed computational schemes to different scenarios.

In-situ investigations were carried out in the Kama reservoir domain 16 km in length. The upper boundary of this region was 3 km upstream from the intake channel, and its lower boundary was 10 km downstream from the mouth of the discharge channel.

A digital relief model (DRM) of the reservoir bottom and its parts was constructed at a scale of 1:10000 for the normal water level at the Kamskaya HPP (108.5 m.abs.) using a professional surveying system. This system consists of a single beam Hydrobox echosounder, a set of Topcon GR-5 GPS GNSS Glonass receivers, and a hydrographical survey software package AquaScanOfficeGG+. Based on the obtained results, a schematic map of the examined area of the reservoir was constructed (Fig. 2).

During the field surveys, temperature measurements were made across the area of the Kama reservoir and through its depth under different meteorological conditions and operating conditions of the Permskaya TPP. The temperature was measured at 1 m-depth increment with the WTW conductivity meters ProfiLineCond 1970i at 16 measurement lines. The measurement points are shown in Fig. 3. Daily processing of a great body of data provided information on the distribution of temperature over the Kama reservoir and through its depth in the region of the Permskaya TPP under specific weather conditions (Figs. 4 and 5).

Meteorological data such as air temperature, wind direction and velocity, humidity, and pressure were recorded (at a 5 min recording interval) in the automatic mode using a Kestrel 4500 portable field meteostation.

Curves of temperature variation with the depth of the water body were plotted in Fig. 5.

2.2. Combined computational approach

In the presence of vertical density stratification, three-dimensional effects play a crucial role in the water dynamics. However, even with the use of modern computational resources, it is impossible to construct a three-dimensional mesh for modeling these effects with sufficient resolution for large water bodies of hundreds of kilometers in length and tens of meters in depth. The development of the combined models may be thought as an effective way to overcome this difficulty. We developed a combined approach including the in-situ measurements and the 1D-, 2D, and 3D numerical simulations. In this approach, the results of 1D modeling are used to formulate boundary conditions for the 2D problem and the results of the 2D modeling are used to formulate boundary conditions for the 3D problem. Solution of a number of important environmental problems solved successfully using this approach [26–29] confirmed that it makes possible to gain information on the considered ecosystem state very quickly which allows to provide effective control of the power plants and prevention of technological and environmental risks.