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THERMAL POLLUTION OF A THERMAL POWER PLANT WITH ONCE-THROUGH COOLING SYSTEMS: A NUMERICAL STUDY

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Abstract. *A two-dimensional numerical model was proposed to simulate the thermal discharge from a power plant in the Republic of Serbia. The impact of the Nikola Tesla B thermal power plant on the Sava River was considered. This thermal power plant uses a once-through cooling system. A two-dimensional model was developed in the Gambit program. This model was later employed in numerical simulations using the Ansys Fluent software package. Flow parameterization was performed to determine the optimal flow of the Sava River. Four scenarios were considered, where scenario 1 represents a flow ratio of the discharge channel and the Sava River of 3% and scenario 4 a flow ratio of 12%. With the appearance of increasing droughts, the flow of rivers also decreases. As the river flow decreases, the ratio of discharge channel and river flow increases. The analysis will show that the higher this ratio, the greater the negative impact on the living world in the river. Namely, there is an increase in the heat load of the river. In the numerical simulations, the initial river temperature was taken as the arithmetic mean temperature in the summer months for the previous five years, before reaching the Nikola Tesla B thermal power plant itself. That temperature amounts to 23.1°C. When scenario 1 is compared to scenario 4, one can notice that by changing the flow of the Sava River and for the same inlet temperature, the river temperature is higher for scenario 4 at the distance of 2000m after the discharge.*

Key words: *Thermal pollution, Thermal power plant, Environmental impact, Wastewater, Numerical simulation.*

1. INTRODUCTION

The total thermal power output of plants in the Republic of Serbia is 5171MW [1]. Lignite is used as a fuel in these thermal power plants. Another 353 MW is produced in

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combined heat and power plants and 2835 MW in hydropower plants. The Republic of Serbia is still not considering the suppression of electricity gained from thermal power plants and plans to build new ones [2]. In Serbia, as much as 70% of thermal power plants use a once-through cooling system from the Danube, Sava and Velika Morava rivers. The thermal power plant with the largest capacity is the thermal power plant Nikola Tesla (TENT). TENT A and B use water from the Sava River to cool the condensers. Both power plants, at full power, take for their technological needs 92 m^3 / sec (331200 m^3/h) of water, of which TENT A takes 52 m^3 / sec (187200 m^3/h) and TENT B 40m^3 / sec (144000 m^3/h).

Once-through cooling systems circulate water through plants a single time to provide cooling during generation. These systems require large volumes of water, which is extracted from rivers, lakes, or oceans [3]. This water is cycled through the cooling system and then discharged, transferring waste heat from the power plant into the discharge water body. The discharge water body is usually the source of the cooling water, causing a local temperature increase. Typical discharge temperatures from once-through cooling systems are 8 to 12°C above intake temperatures, with some systems raising temperatures as much as 15°C [4]. This heated discharge water is then mixed with the receiving water body, with temperature impacts dissipating downstream through radiant transfer or evaporation [5]. Variability between power plant discharge temperatures can be due to differences in local climates, plant efficiencies, or volumes of water withdrawn for cooling [6].

2. THERMAL POLLUTION

Thermal pollution is classified as a water pollutant when it is caused by heated industrial wastewater or anthropogenic (human) changes in coastal vegetation that increase water system temperatures due to solar radiation. A common cause of thermal pollution is the use of water as a coolant in power plants and industrial producers [7]. As a result of high temperatures, these discharges into rivers can cause more than normal levels of organic matter, fecal bacteria, and toxic substances. The resulting increase in biochemical oxygen demand (BOD) can lead to the killing of fish while the high concentrations of fecal bacteria can limit water use. Reduced dissolved oxygen (DO) can cause direct mortality in aquatic organisms or result in subacute effects such as reduced growth and reproductive success [8-10]. Increasing the temperature by just 1°C or 2°C can adversely affect wildlife in rivers because the increase is deadly to some species and can affect their growth and reproduction [11].

Several studies have found a gradual increase in river temperature over the last century relative to an increase in air temperature [12-14]. In addition, the increase of the water temperature is also associated with changes in the river flow [15].

Because rising water temperatures can be dangerous to the environment, for example, the impact on fish populations, in many countries it is necessary to prepare an Environmental Impact Assessment (EIA) before building such facilities. Among many other aspects of EIA, predicting a possible increase in water temperature caused by an artificial heat source is crucial. Such predictions are usually made using numerical models [16].

A sensitivity analysis showed increases in annual mean river temperatures of +1.3°C, +2.6°C, and +3.8°C under air temperature increases of +2°C, +4°C, and +6°C, respectively [17]. Given future perspectives, warming is expected to affect river temperatures and river regime modifications as a result of climate change and other anthropogenic influences (e.g., flow regulation, water withdrawal) [18].

Thermal pollution of natural watercourses by thermal power plants has been studied since the middle of the 20th century [19]. Significant research in this area began with the development of industry and the increased usage of electricity. As the electricity production capacities grow, so does the use of fresh water in the processes of obtaining the energy itself [20, 21]. The occurring climate change has led to more serious research into thermal pollution to reduce the negative impact and pollution of water [22-24]. To protect natural watercourses as much as possible, certain Directives determine the maximum allowed values of surface water temperature worldwide [25,26]. In the USA, the maximum allowed value is 32°C, while for the EU areas the water temperature after discharge from thermal power plants should not exceed 21.5°C and 28°C, i.e. it should not be higher by 1.5°C or 3°C concerning the temperature of the natural watercourse before the intervention in the thermal power plant.

Many studies have proven a great similarity between the results obtained by measuring the heat load of watercourses and making a numerical simulation. First, 2D numerical models were developed [27], and later 3D models were also used [28, 29].

There are several ways to improve the performance of a power plant. One of them is to improve the performance of the cooling system [30]. A change in the cooling water mass flow rate impacts the pressure in the condenser, which affects the power output of the turbine and the power that has to be delivered to the cooling water pump [31]. In this paper, the flow parameterization is performed, i.e. the optimal flow ratio between the discharge channel and the Sava River is analyzed with the help of numerical tools in order to avoid a negative impact on the river by the thermal power plant.

Research as such is rare in Serbia. The thermal pollution of the Danube was considered. It was determined that the temperature of the Danube River increases by about 1°C downstream of the Kostolac thermal power plant [32-34].

3. MATHEMATICAL MODEL OF THERMAL POLLUTION

The mathematical model of thermal pollution is based on Reynolds-averaged Navier-Stokes (RANS) equations. The mathematical form of the RANS equation and the energy equation is [35]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho \overline{u_i})}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho \overline{u_i})}{\partial t} + \frac{\partial(\rho \overline{u_i u_j})}{\partial x_j} = -\frac{\partial(\bar{p})}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial(\overline{u_i})}{\partial x_j} + \frac{\partial(\overline{u_j})}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial(\overline{u_m})}{\partial x_m}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{\grave{u}_i \grave{u}_j}\right) \tag{2}$$

$$-\rho\overline{\grave{u}_i \grave{u}_j} = \mu_t\left(\frac{\partial(\overline{u_i})}{\partial x_j} + \frac{\partial(\overline{u_j})}{\partial x_i} - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial(\overline{u_m})}{\partial x_m}\right)\right) \tag{3}$$

$$\frac{\partial T}{\partial t} + \frac{\partial u_j T}{\partial x_j} = \frac{\partial\left(-\overline{\grave{u}_j \grave{T}}\right)}{\partial x_j} + \frac{\partial}{\partial x_j}\left(D\frac{\partial T}{\partial x_j}\right) \tag{4}$$

where μ_t is the effective turbulent (eddy) viscosity.

The various turbulent models can be applied to close the RANS equations. In these analyses, the k-ε turbulence model was applied.

Turbulence kinetic energy k has its transport equation:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho\overline{u_i}k)}{\partial x_i}=-\rho\overline{\grave{u_i}\grave{u_j}}\frac{\partial(\overline{u_i})}{\partial x_j}-\rho\varepsilon+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \tag{5}$$

This requires a dissipation rate, ε, which is entirely modeled phenomenologically (not derived) as follows:

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\overline{u_i}\varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}P_k\frac{\varepsilon}{k}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{6}$$

Dimensionally, the dissipation rate is related to k and a turbulence length scale L_t:

$$\varepsilon\sim\frac{k^{3/2}}{L_t} \tag{7}$$

Considering the equation (5), eddy viscosity can be expressed as:

$$\mu_t=\rho C_\mu L_t\sqrt{k}=\rho C_\mu\frac{k^2}{\varepsilon} \tag{8}$$

Where:

u_i – velocity components
ρ – fluid density
$\grave{u_i}\grave{u_j}$ – averaged Reynolds velocity stresses
P – fluid pressure
T – fluid temperature
D – thermal diffusivity
$\overline{\grave{u_j}\grave{T}}$ – turbulent heat fluxes
P_k – production of turbulence.

The values of the constants are as follows: $C_{1\varepsilon}=1{,}44$; $C_{2\varepsilon}=1{,}92$; $\sigma_k=1$; $\sigma_\varepsilon=1{,}3$; $C_\mu=0{,}09$.

4. FIELD OF STUDY

TPP "Nikola Tesla B" consists of two identical units, each with a capacity of 620 MW. The condenser cooling system is a once-through system that uses cooling water from the Sava River. After passing through the cooling system, water is collected in a reservoir from which, through concrete channels of rectangular cross-section, it flows gravitationally back into the river. A simplified schematic diagram of the 620MW steam power unit including a steam condenser and an open cooling cycle is shown in Fig. 1.

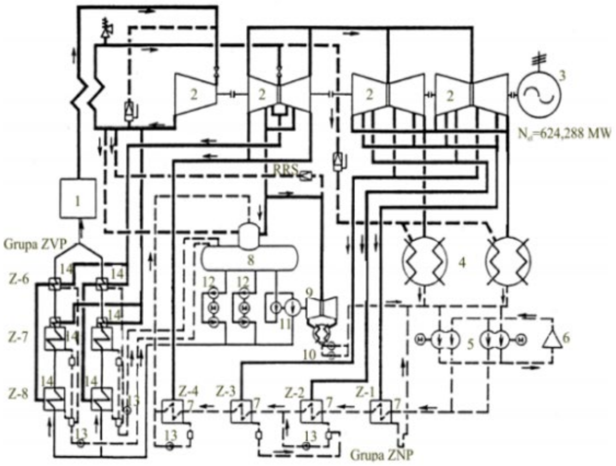

Fig. 1 Simplified developed thermal scheme of a 620 MW power block - TENT-B [36] Legend: 1 - steam generator (boiler); 2 - steam turbine; 3 - electric generator; 4 - condenser; 5 - condensate pumps; 6 - recirculation and purification of turbine condensate; 7 - low pressure heaters; 8 - feed tank with deaerator; 9 - feed pump turbine drive; 10 - turbine condenser feed pump; 11 - main feed booster pumps; 12 - auxiliary feed pumps; 13 - drainage condensate pumps; 14 - high pressure heaters

On the Sava River itself, there are measuring stations where it is possible to obtain the temperatures, flow and water level. Upstream the TENT B is the Šabac measuring station and downstream the thermal power plant is the Belgrade measuring station. Observing the data from these stations, it can be noticed that the average annual temperature for the Šabac measuring station is 12.7°C, while the highest daily temperature is 29°C. When it comes to the Belgrade measuring station, downstream the Nikola Tesla thermal power plant, the average temperature of the Sava River is 13.3 °C, while the maximum daily temperature is 30°C. These data from the measuring stations indicate the existence of a negative impact of the operation of thermal power plants on the Sava River.

Changing the natural climate of the river, more precisely increasing the water temperature, will reduce the oxygen content in the river. And this can lead to the death of aquatic organisms, for which even a little thermal pollution of the environment is critical.

5. NUMERICAL SIMULATION OF THE SAVA RIVER THERMAL POLLUTION

Numerical simulation of the Sava River thermal pollution by mixing hot water from the channel that cools TENT B was done using the Ansys Fluent program. A Semi-Implicit Method for Pressure-Linked Equations (SIMPLE method) for numerical solution was used. The geometric model and discretization mesh were created in the Gambit program. The grid consists of 59 375 elements, all of which are rectangular Quad Map. Around the walls of the river and in the part of the connection of the channel with the river, where the mixing of water in the river itself and water from the channel occurs, the network was additionally densified. Fig. 2 shows the mesh.

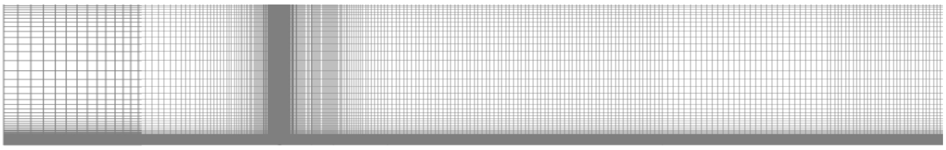

Fig. 2 Discretization mesh

An additional layer is very important when forming a discretization mesh. When forming the mesh, the y^+ concept was used. The y^+ value is a non-dimensional distance (based on local cell fluid velocity) from the wall to the first mesh node, as can be seen in Fig. 2. To use a wall function approach for a particular turbulence model with confidence, it is necessary to ensure that our y^+ values are within a certain range [37].

$$y^+ = \frac{y \cdot \mu_t}{v} \tag{9}$$

In this case, the growth factor of 1.2 was used and applied to the first 4 lines.

In this paper, the river Sava is considered together with the hot water channel discharging the water from TENT B. At the location of TENT B, the river Sava is 400 m wide. The problem of thermal pollution was considered at a length of 2 km. The hot water channel is 6 m wide and 400 m long. The angle that forms the channel with the river Sava is 30 degrees. The geometrical characteristics of the channel are given in Fig. 3.

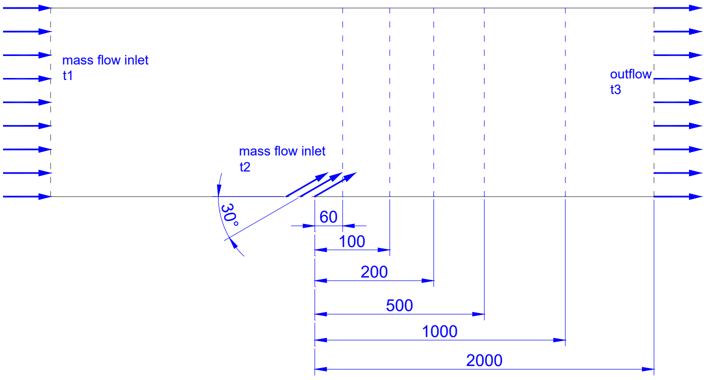

Fig. 3 The geometrical characteristics of the channel

All relevant data were used from the Hydrometeorological Institute of Serbia measuring stations. The data from the Šabac measuring station were used for the numerical simulation. Table 1 shows the average water temperature for the summer period of 2015-2019 [38].

A group of authors who researched the thermal pollution of the Sava River determined that in the summer the river warms up by 9.4°C [39]. Based on this data, the model was set up. The temperature of the channel compared to the temperature of the Sava River was higher about 9.4°C.

Based on data from the Hydrometeorological Institute of Serbia, it was determined that the average temperature in the summer months for the period 2015-2019 was 23.1°C. This temperature was used in numerical simulations to obtain the values of thermal pollution. Numerical simulations were set for convergence criteria of RMS to reach 10^{-6}.

Calculating the water velocities of the Sava River was based on the value of the average water flow upstream the TENT B [40], the cross section of the river, which is given previously in Fig. 3, and the average depth of the Sava River, which is 12 m. The speed in the channel is 2.22 m / s with the constant flow of 40 m^3 / s and the rectangular cross-section of the channel with dimensions of 6 m and 3 m. Parameters used in numerical simulations are given in Table 1. The results of numerical simulations are shown in Table 2.

Table 1. Parameters used in the main scenarios

Scenario	**$Q_{channel}$ / Q_{Sava} [%]**	**Velocity [m/s]**
1	3	0.278
2	6	0.139
3	9	0.092
4	12	0.069

Table 2. River temperature of the mixed water in different cross-sections downstream the junction area

Scenario		**Distance [m]**					
		60	**100**	**200**	**500**	**1000**	**2000**
1	**River temperature [°C]**	24.789	24.796	24.750	24.785	24.754	24.608
2		24.810	24.829	24.830	24.912	24.885	24.747
3		24.819	24.842	24.860	24.959	24.936	24.801
4		24.852	24.858	24.897	24.995	24.967	24.831

The following figures show the velocity vectors for all four scenarios as well as the temperature contours for the first and the fourth scenario.

If comparing the velocity vectors, one can notice that in scenario 1 they flow naturally because the velocity of the Sava River is satisfactory. However, as the speed of the Sava River decreases and thus the flow of the river with it, the hot water channel has an increasing influence on the water in the river. This way, hot water takes precedence in the mixing zones and has a more dominant role. Therefore, this leads to the fact that the temperatures from the hot water channel affect the temperatures in the river more. Numerical simulations show that the water temperature at all sections of the measurement is higher in all scenarios compared to the first scenario. If comparing scenario 1 with scenario 4, one can notice that by changing the flow of the Sava River at the same inlet temperature at 2000 m distance from the confluence, the river temperature is higher by 0.23°C. As the laws on endangering the environment are becoming stricter, any reduction in water temperature is very significant. One should bear in mind that the reduction of the flow is directly related to the temperature of the water. This analysis was performed with a constant water temperature of 23.1°C.

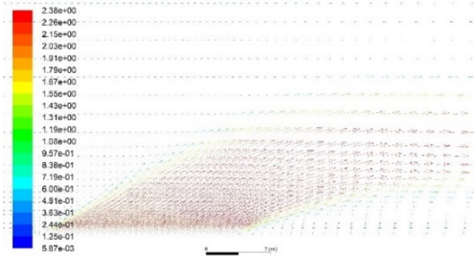

Fig. 4. Velocity vectors - scenario 1

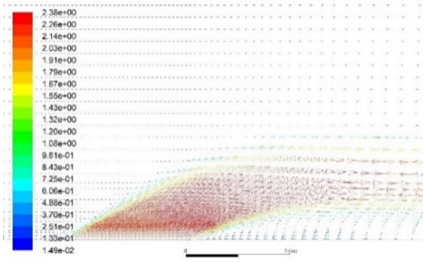

Fig. 5. Velocity vectors - scenario 2

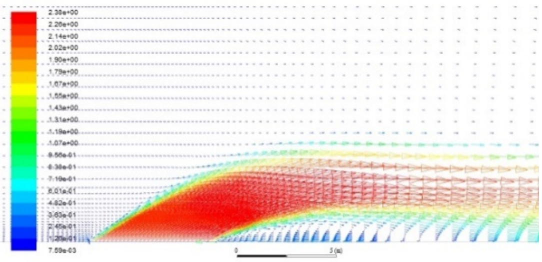

Fig. 6. Velocity vectors - scenario 3

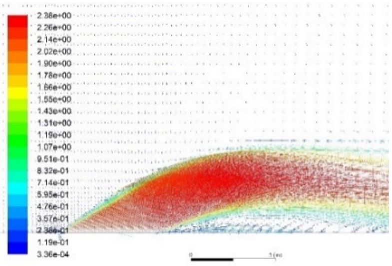

Fig. 7. Velocity vectors - scenario 4

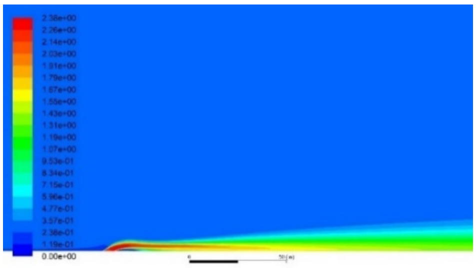

Fig. 8. Temperature contours - scenario 1

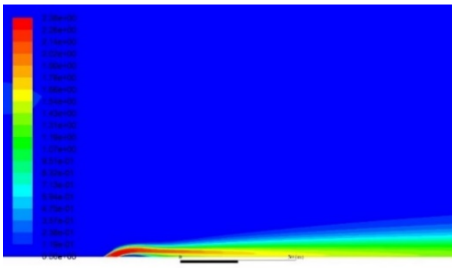

Fig. 9. Temperature contours - scenario 4

CONCLUSION

Thermal power plants use large amounts of water in their processes. During that use, they pollute the waters. This paper defines and discusses the thermal pollution of the Sava River caused by the operation of the Nikola Tesla B thermal power plant in the Republic of Serbia.

The presented problem is solved numerically by analyzing the ecological situation of the river for different flow ratios of the discharge channel and the river. For numerical analysis, four problems were set, and four scenarios were solved and analyzed. Based on the mathematical and numerical model, water temperature, river flow and water velocity, the analysis of thermal pollution of the river at certain distances from the thermal power plant was performed.

Based on the obtained numerical results, one can determine the existence of thermal zones on the right bank of the Sava River, downstream from the Nikola Tesla B thermal power plant where the heated water discharge channel is located. The flow channel and the Sava River flow parameterization were performed. Four scenarios were considered, with a constant discharge channel flow of 40m^3 / s being taken for each scenario. Numerical results have shown that with the decrease of the river flow, the temperature of the Sava River increases. Comparing the most optimal (scenario 1) and the most unfavorable scenario (scenario 4), the temperature increase is determined by 0.23°C at 2 km distance downstream the Nikola Tesla B thermal power plant. This temperature increase is significant for the living world in the river. This may represent temperature shock and have a negative impact.

The following research should be conducted in the direction of increasing the initial temperature of the river. With the drop in the initial water flow and the subsequent drop in the speed of water in the river, the higher water temperatures occur. Namely, scenario 1 can be realized in the months that do not include the summer period. With higher initial river temperatures, above 23.1°C, the thermal pollution of the water will be even more pronounced.

Similar research in the field of thermal pollution should be continued in the future. With the obtained numerical data, it will be possible to precisely specify in advance the impact on the environment from the operation of a thermal power plant. In such a way, the location of the planned thermal power plant could be chosen, but also a decision could be made on which cooling system to use in the thermal power plant to avoid environmental disasters.

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