THE NUMERICAL APPROACH OF THERMAL POLLUTION FROM THERMAL POWER PLANTS

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Abstract: This paper presents the results of numerical simulations of thermal pollution from the thermal power plant Nikola Tesla B, which uses the Sava River to cool the condenser. A 2D model was developed in the Gambit program which was later used in numerical simulations using the Ansys Fluent software package. During the formation of the model, meteorological and hydrological data were used, as well as the operating parameters of the considered thermal power plant. The analysis of the existence of thermal pollution in the coastal part of the Sava River, downstream from the thermal power plant, was considered for the summer period from 2015-2019. The summer months were used because it was during that period that the capacity of rivers decreased and temperatures increased. The depth of the Sava River was not considered during the simulations. Mass flow of Sava River and effluent channel were used as boundary conditions. In these analyses the depth of Sava River is not considered. The results showed the existence of thermal pollution of the Sava River by the thermal power plant along the right bank. The increase in temperature in the summer months is also significant in the dry years when the flow of the Sava River decreases, the water temperature rises by more than 2° C. With very high temperatures, the living world in the water is endangered.

Key words: thermal pollution, thermal power plant; environmental impact; wastewater, numerical simulation

1. INTRODUCTION

Electricity can be obtained from both fossil and renewable fuels. According to data from 2019, as much as 75.5% of the total electricity produced in the world, comes from fossil fuels (coal 38.3%, natural gas 23.1%, oil 3.7%, and nuclear 10.4%) [1]. Thermal power plants which use coal and natural gas as fuels comprises approximately 61.4% of the total electricity, coming in second place are hydroelectric power plants with a share of 16.6% and in third are nuclear power plants with 10.4% [2].

China ranks first in terms of installed capacity with 1004948 MW, in second place is the US with 246187MW and then India with 228964MW [3]. Electricity generation from fossil fuels continues to dominate in Europe (74% in 2017) [4]. In Europe, the most installed power is located in Germany 44470MW, Poland 30870MW, Turkey 18000MW.

In countries in the region, Romania has 12247MW of installed capacity in thermal power plants, then Greece follows with 8804MW, Bulgaria 7963MW, Hungary 7579MW [5].

There is a strong correlation between the growth of industrial production and the growth of electricity consumption [6]. This leads to the already known conclusion that electricity generation is a key industry in modern industrial society.

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The energy sector uses between 10-15% of fresh water in its plants. Most water is used in the process of producing electricity, about 88%, especially for cooling systems at thermal power plants [7]. Thermal power plants can use surface water, groundwater, and treated water in their processes [8]. Cooling systems used in thermal power plants can be open (once-through) and closed (re-circulation) systems [9]. Once-through systems use water from sources (e.g., oceans, rivers, lakes, or ponds for cooling) as a coolant and then return the water to the sources from where it was taken [10]. With a closed cooling system, the thermal power plant withdraws water, then the water circulates inside the system, where it is not being returned to the water source from where it was taken. The energy efficiency of power plants with once-through cooling is higher up to 5%, compared to plants with a closed-cycle cooling, due to lower temperature of the cooling water [11], but keep in mind that closed cooling systems do not necessarily need a great source of cooling water. Water consumed in a one-through cooling system is negligible (about 1%) [12].

The total thermal power output of plants in the Republic of Serbia is 5171MW [13]. Lignite is used as a fuel in these thermal power plants. Another 353 MW is produced in combined heat and power plants and 2835 MW in hydroelectric power plants. The Republic of Serbia is still not considering the suppression of electricity gained from thermal power plants and plans to build new ones [14]. In Serbia, as much as 70% of thermal power plants use a once-through cooling system from the Danube, Sava, and Velika Morava. The thermal power plant with the largest capacity is thermal power plant Nikola Tesla.TPP Nikola Tesla A and B use water from the Sava River to cool 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).

2. THERMAL POLLUTION

Water quality can be changed as a result of natural and anthropogenic processes that take place in the environment. Some of these processes result in the degradation of water quality due to an increase in temperature, the concentration of elements, or the appearance of nitrogen and phosphorus compounds [15].

Thermal pollution is discerning the quality of the water using any action which changes the temperature of the ambient water [16]. With the temperature increase, oxygen in the water is reduced thus directly affecting the ecosystem of the water source itself [17].

Thermal pollution wasn't considered a big pollutant of ecosystems at first. Research in this particular area starts in 1960 and precisely the thermal pollution which comes from thermal power plants was taken into consideration because it turned out that they are the biggest polluters of the water [18]. Once the problem was exposed, a group of authors started to research the area based on meteorological data for a specific area [19]. Special attention is paid to understanding water temperature through sensitivity analysis [20].

Some studies are focused on the connection between the increase in demand for electricity and wastewater [21,22]. Others connect climate change and the workings of the thermal power plants pointing that for the plant to work, it depends on the water temperature, increasing the temperature the production and efficiency of the power plant itself are reduced [23]. Similar studies but for different localities were done by [24, 25].

Some of the studies only dealt with the influence of only one thermal power plant [26], whilst there are analyses and effects of more thermal power plants connected to one power source [27].

Thermal pollution of freshwater natural watercourses due to the operation of thermal power plants is more pronounced in thermal power plants with a once-through cooling system [28]. In contrast with closed cooling systems, where almost all the heat absorbed during the steam cycle is removed via evaporation and dissipated into the atmosphere, once-through cooling involves the direct rejection of the heat back into the water body [29]. As there are several thermal power plants along one river that use water from the same river to cool condensers, the whole process of planning the construction of new thermal power plants and the use of water from the same river in a certain domain is further complicated. [30]. To protect natural watercourses as much as possible, certain Directives in the world determine the maximum allowed values of surface water temperature [31,32]. In the US, the maximum allowed value is 32 ° C, while for EU countries, 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 than 1.5 ° C or 3 ° C concerning the temperature of the natural watercourse before withdrawal in the thermal power plant.

In recent years, numerical tools to predict and calculate thermal pollution are used. The usage of numerical tools to predict thermal pollution began in 1978 by McGuire and Rode [33]. They developed 2D models. In 1987, a 2D model of thermal pollution for the coastal part of the river was developed [34]. The speed of water leaving the thermal power plant and flowing into the river was also analyzed, as well as the angle at which hot water enters the river [35]. Using a 2D and 3D model, a group of authors presented the zones of thermal pollution of the operation of three thermal power plants [36]. Alibek Issakhov [37] also examined the influence of thermal power plants on the formation of thermal zones in the river. A 3D hydrodynamic model was used to test the thermal pollution of the Permskaya GRES thermal power plant in Russia [38].

In this paper, the influence of meteorological factors on the formation of temperature fields was considered. A group of authors [39] found that in the summer months, in thermal power plants that use a once-through cooling system of condensers, the river temperature is increased by 9.5-10 ° C. This research was done in the US. There is a large dependence of water temperature on air temperature [40], only by the action of meteorological conditions. This dependence is 7 ° C in summer while in winter it is 5 ° C. The summer period is of great interest for researching the thermal pollution because then there is a large consumption of electricity, while the water of the river is at a higher temperature [41].

In Serbia, the thermal pollution of the Danube was considered and it was determined that the temperature of the Danube River rises by about 1 ° C downstream of the Kostolac thermal power plant. [42,43,44].

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 [45]:

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

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

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

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

$\mu_t -$ an effective turbulent viscosity (Eddy viscosity)

The k-e turbulent model was used for solving RANS equations. The turbulent k-e model was first used by F.H. Harlow and P. Nakayama in 1968 [46]. Turbulence energy k has its transport equation:

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

Together with the k equation, eddy viscosity can be expressed as:

$$\mu_t = \rho C_\mu L_t \sqrt{k} = \rho C_\mu \frac{k^2}{\varepsilon} \quad (6)$$

Where:

ui – the velocity,

ρ – the density of the fluid,

$u_i^` u_j^`$ – averaged Reynolds velocity stresses,

P – the fluid pressure

T - fluid temperature,

D - thermal diffusivity

$\overline{u_j^` T^`}$ -turbulent heat fluxes

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. NUMERICAL SIMULATION OF THERMAL POLLUTION OF THE SAVA RIVER

Numerical simulation of thermal pollution of the Sava River by mixing hot water from the channel that cools TPP Nikola Tesla B was done using the Ansys Fluent program. A Semi-Implicit Method for Pressure-Linked Equations (SIMPLE method) in numerical simulations is 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 canal with the river, where are a mixing of water in the river itself and water from the canal, the network is additionally densified.

In this paper, the river Sava is considered together with the hot water channel coming from TPP Nikola Tesla B. The problem was considered for the summer period when due to high temperatures, the temperature of the Sava River increases, and at the same time, the river flow decreases. At the location of TPP Nikola Tesla 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 6m wide and 400m long. The angle that forms the canal with the river Sava is 30 degrees. The geometrical characteristics of the channel are given in Figure 1.

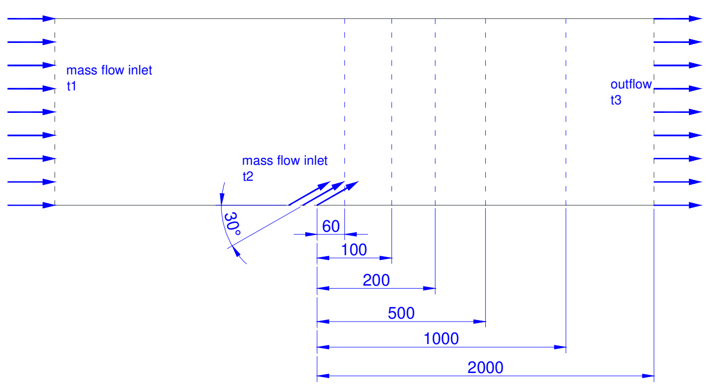


Figure 1. The geometrical characteristics of the channel

All relevant data were used from the measuring stations of the Hydrometeorological Institute of Serbia. In front of the thermal power plant Nikola Tesla B, there is a measuring station Šabac. The following table shows the data for the summer period from 2015-2019 [47].

Table 1. Average water temperature and average water flow rate upstream the TPP

Šabac							Belgrade		
YEAR	Average water temperature [°C]			Average water flow rate [m^3/s]			Average water temperature [°C]		
	July	Aug.	Sept.	July	Aug.	Sept.	July	Aug.	Sept.
2015	24.4	24.6	21	634	454	470	27.4	28.7	22*
2016	23	22.9	20.7	865	670	612	24.9	25.1	22.7
2017	24.9	24.3	18.9	494	362	817	27.9	27.3	22.2
2018	20.1	23	20.5	1180	669	535	22.8	26.6	23.4
2019	21.7	22.8	19.7	701	536	491	26.1	27.1	23.5

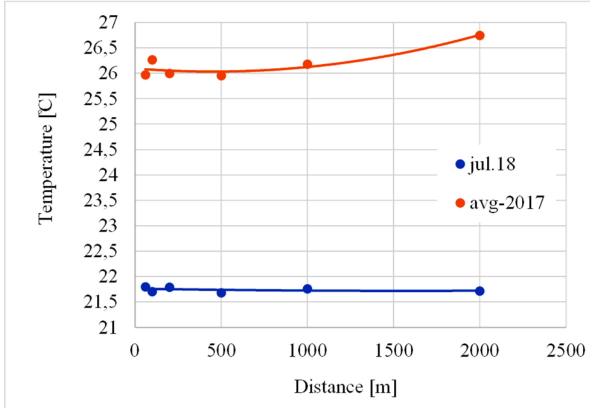
*- lack of data for all days of that month

Based on the available data, it can be concluded that the water temperature, in the summer period, after passing through the cooling system increases by an average of about 9.4 °C [48]. Based on this data, the model was set up so that the temperature of the channel compared to the temperature of the Sava River was higher about 9.4 ° C. Table 2 shows the values of the Sava River temperature obtained using numerical simulation. Values were recalculated using the Integral Facet Average method.

Table 2. Water temperatures of Sava River downstream the junction

Year	Month	Distance[m]	60	100	200	500	1000	2000
2015	July	Temperature [°C]	26.008	26.115	26.022	26.277	26.4	26.832
	Aug.		26.22	26.372	26.262	26.484	26.644	27.183
	Sept		22.808	22.627	22.672	22.907	23.07	23.9
2016	July	Temperature [°C]	24.685	24.803	24.688	24.642	24.657	24.828
	Aug.		24.548	24.779	24.576	24.815	24.559	24.652
	Sept		22.363	22.498	22.797	22.404	22.565	22.499
2017	July	Temperature [°C]	26.604	26.802	26.728	26.53	26.853	26.908
	Aug.		25.971	26.267	25.998	25.953	26.179	26.747
	Sept		20.64	20.77	20.574	20.491	20.658	20.673
2018	July	Temperature [°C]	21.798	21.705	21.79	21.682	21.758	21.717
	Aug.		26.665	24.65	24.77	24.843	24.923	25.233
	Sept		22.27	22.318	22.11	22.289	22.468	22.83
2019	July	Temperature [°C]	23.497	23.702	23.376	23.328	23.399	23.589
	Aug.		24.489	24.655	24.774	24.459	24.759	24.645
	Sept		21.382	21.79	21.355	21.361	21.634	21.513

The flow of the Sava River is directly related to the river temperature. After numerical simulations, it was determined that with a higher flow of the Sava River there are very small oscillations in the temperature change after mixing with the hot water channel. While when there are dry periods and the flow of the river is small, then after mixing there are big temperature changes. A comparative analysis was performed for July 2018, when the highest flow of the Sava River was in the period between 2015-2019 and amounted to 1180 m^3/s, and for August 2017, when the flow was only 362 m^3/s. The following diagram shows this comparative analysis.



Numerical simulations showed that in the first case, there is a temperature increase of 1.6 ° C, while in the second case the temperature increase was as high as 2.4 ° C. Another important difference is that in July 2018, after mixing the Sava River with the hot water channel, the temperature was approximately the same on all measurement sections, i.e., it differed from the initial section, which was located 60 m from the mixing to the section that was set at 2000m is negligible. If the same comparison is made for the second case, a greater oscillation of the temperature of the Sava River is observed, from the initial distance of 60 m to the final temperature differs by approximately 1 ° C. This indicates that there is a relationship between the flow of the Sava River and the flow of hot water channels. It is necessary for this relationship to be optimized in order to minimize the heat load of the river and thus effectively minimize the danger it presents to the ecosystem in the river itself as well as in the coastal part.

The obtained temperature changes on the surface of the Sava River are shown in the following figures, for the period August 2017 and July 2018. The presented results show the change in the temperature of the Sava River along the right bank of the river.

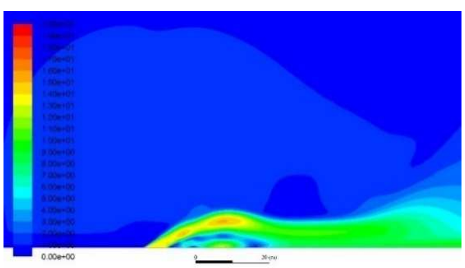


Figure 2a. Contours of velocity for August 2017

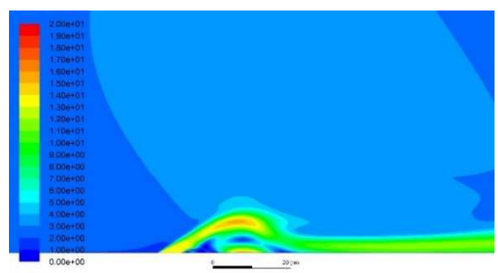


Figure 2b. Contours of velocity for July 2018

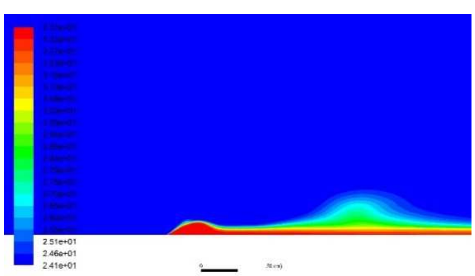
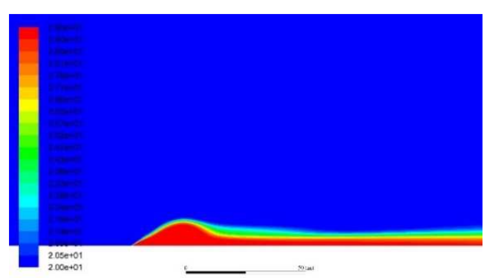


Figure 3a. Contours of temperature for August 2017



3b. Contours of temperature for July 2018

From the pictures of the velocity vectors for these two scenarios, it can be concluded that the mixing zone in July 2018 is much milder compared to August 2017.

If the previous two images are analyzed, it can be seen that when the flow of the Sava River is reduced, there are more so-called thermal zones, the mixing zone is much more pronounced. When the flow of the Sava River is high enough, then along the right bank of the river there is a much calmer flow and the temperature field is evenly distributed.

It is very important to note that 17 km from TPP Nikola Tesla B is TPP Nikola Tesla A which also uses water from the Sava River for the needs of the cooling system. This implies that the thermal pollution of the Sava River by TPP Nikola Tesla B directly affects the efficiency of TPP Nikola Tesla A. In the part between these two thermal power plants, there are no measuring stations to read the temperature of the Sava River after passing by TPP Nikola Tesla B.

The measuring station exists after TPP Nikola Tesla A and that is the measuring station Belgrade.

If compare the temperatures from the measuring stations Šabac and Belgrade, it will be noticed that the temperatures from the measuring station Belgrade are always higher. This indicates the existence of thermal pollution of the Sava River from the thermal power plants Nikola Tesla A and Nikola Tesla B.

5.CONCLUSION

In this paper, the thermal pollution of the river caused by the operation of thermal power plants is analyzed. The impact of TPP Nikola Tesla B on the Sava River in the length of 2 km downstream from the thermal power plant in the summer period was considered. The Ansys Fluent software package was used to obtain numerical simulations.

The obtained results show the existence of thermal pollution of the Sava River by TPP Nikola Tesla B, downstream from the thermal power plant along the right bank of the river. In the summer months, the level of the Sava drops a lot and then the reduced level of the river additionally affects the appearance of thermal pollution. In the days of high temperatures and reduced levels of the Sava River, the temperature rises downstream from the Nikola Tesla B thermal power plant by as much as 2.4 ° C. Also, the relationship between the flow of water in the canal and the flow of the Sava River is very important. This analysis found that this ratio should not exceed 3%. In these analyses the depth of Sava River is not considered.

Numerical simulations of thermal pollution of rivers are a very reliable and useful tool for analyzing the distribution of temperatures, velocities, zones of mixing of two streams of water. During the next analysis, it is necessary to take into account the depth of the Sava River and thus the speed of the river. In that way, a more complete picture of the formation of thermal zones would be obtained. As the construction of another thermal power plant on the Sava River is planned, it is necessary to consider the use of combined cooling systems. In the summer months, a plant operates with a cooling tower and in that way, the additional negative impact of the thermal power plant on the ecosystem of the Sava River is reduced.

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