MATHEMATICAL AND CFD METHODS FOR PREDICTION OF THERMAL POLLUTION CAUSED BY THERMAL POWER PLANT

by

Milica JOVČEVSKI[a*]***, Mirjana S. LAKOVIĆ***[a]***, Iliya K. ILIEV***[b]***, Miloš J. BANJAC***[c]***,***
Filip STOJKOVSKI[d]***, and Marko MANČIĆ***[a]

[a] Faculty of Mechanical Engineering, University of Niš, Niš, Serbia
[b] Department of Thermotechnics, Hydraulics and Environmental Engineering, University of Ruse, Ruse, Bulgaria
[c] Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia
[d] Iskra Impuls, Kranj, Slovenia

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Wastewaters from power plants is a major concern for environmental protection. After the water is used in thermal power plant, the heated effluent is again discharged in the same water body from where it is taken. This not only disturbs the aquatic life but also affects the balance of the ecosystem. This paper presents the background of the thermal pollution, modelling approach and analysis methods for prediction of thermal pollution. A 2-D model of Sava River is discussed. The thermal power plant Nikola Tesla B was considered. Analysis of thermal discharge into the Sava River for the twelve-year period has been carried out. It was done a comparative analysis of the results obtained using mathematical (Electricity of France – EDF) method and numerical analysis using the CFD software package ANSYS FLUENT. A comparison of these two methods was made in order to show that it is possible to predict thermal pollution precisely and that it is possible to apply these methods in the design of industrial plants and not only in large thermal power plants. Finally, the results showed the matching of the obtained values at greater distances from the water outlet of the thermal power plant.

Key words: *thermal pollution, thermal power plant, environmental impact, EDF method, CFD method*

Introduction

Today's biggest problem is environmental pollution. Serbia is one of the signatories of the Green Agenda undertook to implement plans for sustainable transport, clean energy, and environmental protection within the energy sector, as well as a strategy for adapting to climate change [1]. It is very important to use different sources of energy production. The energy mix is mainly considered as a function of technologies and basic economic parameters, to obtain a cost-effective combination of available energy technologies needed to meet energy demand in a certain area [2].

In the Republic of Serbia, most of the electricity is obtained from coal (lignite) [3]. Due to the extremely high dependence on coal, the transition towards clean and RES is

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[*] Corresponding author, e-mail: milica.jovic@masfak.ni.ac.rs

necessary. However, it is necessary to strive for thermal power plants that use lignite as fuel to work as efficiently as possible and with as little negative impact on the environment as possible.

A large amount of water is used in thermal power plants. Water is mainly taken from nearby natural watercourses such as rivers, lakes, and seas. Water is used to cool the condenser of the thermal power plant. Depending on the type of cooling system there are once-through and closed cooling systems. Water-cooled condensers, obviously have some significant advantages over air-cooled systems, primarily in terms of higher specific heat and higher density of the coolant, and, as a rule, lower coolant temperatures [4].

After the water is used in the thermal power plants for the process of cooling the condenser, it returns to the natural waterways as wastewater with an elevated temperature. Adding heated wastewater may not significantly increase the overall temperature of water bodies, but it will increase the local temperature at the point of discharge. This type of pollution is called thermal water pollution.

To indicate the existence of this problem, this paper used the mathematical EDF method and the CFD model and results obtained from the analysis were compared. By using these methods, it is possible to predict whether or not there will be thermal pollution of water due to the operation of thermal power plants. The need for such an analysis is very important to see possible environmental problems even before the construction of a power plant.

Thermal pollution

Thermal pollution is the deterioration of water quality by any process that changes the temperature of the ambient water. An increase in temperature of only 1 °C or 2 °C can harm the living world in rivers because an increase in water temperature is lethal for some species and can affect their growth and reproduction [5]. Water temperature is directly related to the amount of dissolved oxygen (DO) in the water. Any increase in water temperature leads to a decrease in the amount of oxygen.

Heat is classified as a water pollutant when it is caused by heated industrial wastewater or anthropogenic (human) changes in the vegetation on the banks of watercourses that increase the temperature of the water system due to solar radiation. A common cause of thermal pollution is the use of water as a refrigerant in power plants and industrial producers [6].

All power plants and industries need water for cooling. This cooling water is heated in this way and returned to natural flows when heated. Thermal power plants discharge hot water to the same water body from which it is taken since these water bodies are considered as an infinite cooler. The addition of heated wastewater may not significantly increase the total temperature of water bodies, but it will increase the local temperature at the point where it is discharged. Figure 1 presents thermal pollution from power plants and its impact on the environment.

Elevated water temperature adversely affects the ecosystem of the watercourse itself (rivers, lakes, seas, and oceans). Reduced DO can cause direct mortality in aquatic organisms or result in subacute effects such as reduced growth and reproductive success [7-9]. If the heating of the water continues, it will create anaerobic conditions. In addition, surface water algae also grow in warm water conditions and are likely to reduce the level of DO in the water [10]. Figure 2 presents the dependence of oxygen in water with a temperature of that water.

As a result, high temperatures can cause more than normal levels of organic matter, fecal bacteria, and toxic substances in waters affected by heat pollution. The resulting increase in biochemical oxygen demand can lead to the killing of fish, and high concentrations of fecal bacteria can limit water use.

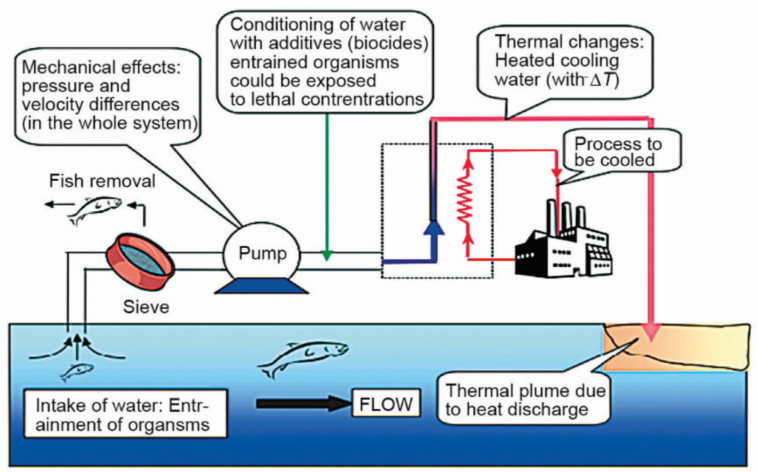

Figure 1. Sketch of a cooling water cycle and its environmental impact [11]

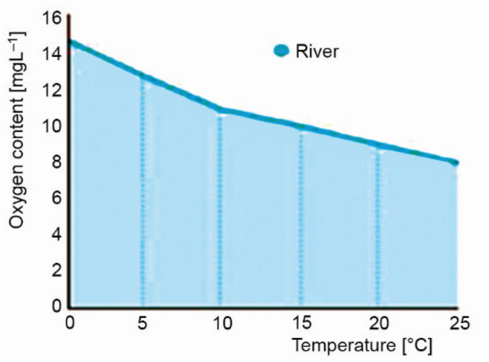

Figure 2. Dependence of water temperature and oxygen content [12]

At present, the increasingly serious problem of water/air pollution has attracted extensive attention from academic and industrial communities. It has become a major environmental problem, affecting all aspects of human production and life [13].

Several studies have found a gradual increase in river temperature over the last century concerning the increase in air temperature [14-16]. Some studies focus on the relationship between the increase in electricity demand and water consumption [17, 18]. Apart from thermal pollution, there are also thermal oscillations. Thermal oscillations may cause a premature critical heat flux, high-pressure drops, control and operational problems, and mechanical vibrations of the system components [19].

In recent times, more and more people are resorting to the use of numerical tools in predicting and calculating the impact of thermal pollution on watercourses. Many studies have proven a great similarity between the results obtained by measuring the heat load of watercourses and making a numerical simulation.

The use of numerical tools for thermal pollution prediction began in 1978 by McGuire and Rodi [20]. They were developing 2-D models. In 1987, a 2-D thermal pollution model was developed for the coastal part of the river [21]. Numerical analysis of heat pollution only spread, so it began with the examination of the influence of water flow and heat exchange after the discharge of heated water into the river.

The velocity of the water leaving the thermal power plant and flowing into the river was also analyzed, as was the angle at which the hot water enters the river [22]. Through analysis, they concluded that the angle at which hot water is discharged into the river has a strong influence on the temperature field of the river. As the angle at which the hot water is discharged decreases, the temperature field is more suitable. Using 2-D and 3-D models, a group of authors presented zones of thermal pollution from the operation of three thermal power plants [23]. Issakhov and Zhandaulet [24] also examined the influence of thermal power plant operation on the formation of thermal zones in the river. In that paper, the influence of different velocities of warm water on the Irtysh River was analyzed. It was established that there is considerable heat pollution on the left bank of this river. A 3-D hydrodynamic model was used to investigate the thermal pollution of the Permskaya GRES thermal power plant in Russia [25].

Due to the impact of climate change, more and more people are resorting to predicting the temperature of natural watercourses. Rajesh and Rehana [26] in they analysis of the impact of climate change on rivers in India presents several prediction models. The best-known and most widely applied water quality prediction model is QUAL2K [27, 28]. However, such a study is specific to the watershed or river section, the data and limits the application to rare and non-measurable locations [29].

A climate of global warming has also shown a negative impact of increasing air temperature on river temperature [30-32]. The summer period is very important for the operation of the thermal power plant because then the temperatures are high and the water flow is reduced. Madden *et al.* [33] determined that in the summer months, at thermal power plants that use a flow condenser cooling system, the temperature of the river warms up by 9.5-10 °C. This research was done in the US. With this increase in temperature comes a significant impact on the living world in the river. There is a great dependence of the water temperature on the air temperature [34], only due to the influence of meteorological conditions. That dependence amounts to 7 °C in the summer period, while in the winter period, it is 5 °C. The summer period is of great interest for heat load research because then there is a large consumption of electricity, and the river water itself is at a higher temperature [35].

Climatic characteristics of the considered area

Meteorological data on the area around TPP Nikola Tesla B were taken from the website of the Republic Hydrometeorological Service of Serbia [36]. About 2 km before the thermal power plant, there is the measuring point Beljin, while downstream of the thermal power plant is the measuring point Belgrade. Since there are only five years of water temperature data for the measuring site Beljin, data were taken from the Šabac measuring station to have a better insight into the temperatures of the Sava River before reaching the Nikola Tesla B TPP itself. If compare the temperatures from tab. 1, it can be concluded that the temperature of the Sava River downstream of the Nikola Tesla thermal power plant is higher compared to the water temperature before reaching the water intake.

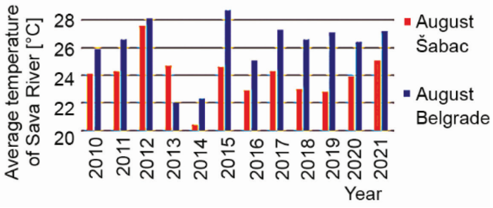

Figure 3. Comparative characteristics of the temperatures of the Sava River

Figure 3 shows a comparative analysis of temperatures in the Sava River for August. In most cases, the difference between these temperatures is over 2 °C. The year 2014 has lower temperature values, and the reason for that is that there were huge floods in Obrenovac that year.

Table 1. Average water temperatures upstream and downstream of the thermal power plant Nikola Tesla B

	Šabac			Belgrade		
Year	The average temperature of Sava River					
	July	August	September	July	August	September
2010	22.5	24.1	18.2	23.5	25.9	20.3
2011	24.1	24.3	22.4	26.5	26.6	25.7
2012	27.3	27.6	23.4	27.9	28.1	23.2
2013	23.5	24.7	19.3	28	22	16.5
2014	22	20.4	16	23.8	22.3	17.4
2015	24.4	24.6	21	27.4	28.7	22*
2016	23	22.9	20.7	24.9	25.1	22.7
2017	24.9	24.3	18.9	27.9	27.3	22.2
2018	20.1	23	20.5	22.8	26.6	23.4
2019	21.7	22.8	19.7	26.1	27.1	23.5
2020	22.7	23.9	21.6	24.7	26.4	23.7
2021	25.6	25.1	20.3	27.1	27.2	22

Methodology

This paper presents two determinations of thermal pollution that occur as a result of the operation of thermal power plants. The first method is the EDF method, which is based on the mathematical interpretation of thermal pollution. Another method is a numerical model. These two methods were compared to show that by using such methods it is possible to indicate the possibility of an environmental problem at a certain location.

The EDF method of calculating the temperature of the river downstream of the hot water outlet from the thermal power plant

The EDF Group developed a mathematical model of water temperature changes in the river environment. This model consists of a formula with an exponential factor and has the form [37]:

$$\Delta t = \Delta t_{\max}\, \mathrm{e}^{-Kx} \tag{1}$$

where Δt [°C] is the river temperature downstream from the hot water outlet from the thermal power plant, $\Delta t_{\max}$ [°C] – the maximum warming of the river caused by hot water discharge, K [km^{-1}] – the factor of the climatic area, and x [km] – the distance.

Coefficient k has values 0.001-0.01. Depending on the region, it is necessary to examine which value of this coefficient corresponds to the given area. Kaushal *et al.* [14] determined that for the area of Romania, the most adequate coefficient is 0.004 1/km.

For the considered reference plant Nikola Tesla B, the results obtained by applying the EDF model for different values of the climatic area factor are presented. The temperature of the Sava River was adopted as 23.1 °C as the mean arithmetic mean of the temperature recorded during the summer period. During the cooling process of the condenser, the temperature of the water warms up by 9.4 °C [38]. There are specific models of hot water channels pouring into the river, such as the case with the channel at the Nikola Tesla B thermal power plant, which is located, due to its length, in the river itself. During the numerical simulations, it was used as if the channel were on the coast due to the simplification of the model. Table 2 presents obtained results. Figure 4 shows how the inflow of the hot water channel into the Sava River at the Nikola Tesla B thermal power plant looks.

Table 2. Results of the EDF method

K [km^{-1}]	River temperature [°C]	Distance [m]						
		60	100	200	500	1000	2000	45000
0.002		32.5	32.49	32.49	32.47	32.44	32.37	29.7
0.003		32.49	32.49	32.48	32.45	32.4	32.31	28.4
0.004		32.49	32.49	32.47	32.44	32.37	32.24	27.15
0.005		32.49	32.48	32.47	32.42	32.34	32.18	25.95
0.006		32.49	32.48	32.46	32.4	32.31	32.11	24.81
0.007		32.49	32.48	32.45	32.39	32.27	32.05	23.72

Figure 5 shows the comparative results of the Sava River temperature obtained using the EDF method.

Figure 4. Realistic representation of the inflow channel and the Sava River at the thermal power plant Nikola Tesla B

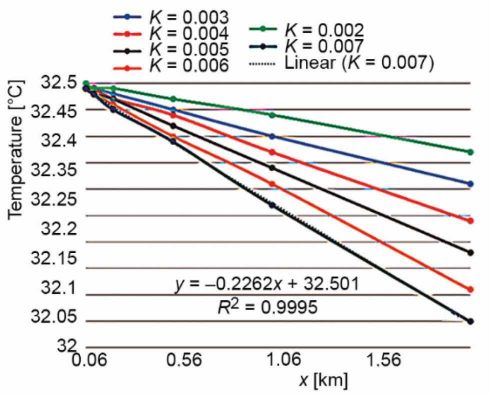

Figure 5. The EDF method for different climate factors

By comparing the result, it can be noted that for the territory of the Republic of Serbia, the climate factor would correspond to 0.007 1/km. Namely, it can be seen that the results obtained by the EDF method are linear character. This method is suitable for longer distances from the outlet of the hot water channel into the river itself. In the zone located at the outlet itself, this method gives approximately the same results for different climatic factors.

When applying the EDF method, the main problem comes down to setting boundary conditions. The precipitation from the Hydrometeorological Institute of the Republic of

Serbia was used as a boundary condition. Namely, based on data from measuring stations located on the Sava River itself, it was found that the water from Obrenovac to Belgrade warmed by about 1 °C. In the calculation of the EDF method, this data was used to determine the climate factor *K*. As the thermal power plant Nikola Tesla, A, is located between the thermal power plant Nikola Tesla B and Belgrade, and its thermal pollution is not the subject of this research, the boundary condition for determining the climate factor was that the temperature of the Sava River near Belgrade should be the same as near Obrenovac.

Numerical analysis

Numerical simulations were carried out on the junction of the Sava River and the effluent cooling water channel. The numerical model was calculated using the FLUENT software package. The boundary conditions used in this model are the input of the mass-flow and temperature of the water in the Sava, mass flow, and temperature at the entrance to the effluent channel. The temperature values are the same as with the EDF method.

Using this combination of mathematical models, the following numerical model was built in 2-D space. A longitudinal section of around 2 km was examined of the Sava River and the effluent channel, considering that this length is suitable for analysis of water mixing and determining the mixing length and intensity, and temperature distribution.

The mathematical model of thermal pollution (CFD) is based on RANS equations. The mathematical form of the RANS equation and the energy equation is presented in [39]:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho \overline{u_i})}{\partial x_i}=0 \tag{2}$$

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

$$-\overline{\rho \grave{u}_i \grave{u}_j}=\mu_t\left\{\frac{\partial(\overline{u_i})}{\partial x_j}+\frac{\partial(\overline{u_j})}{\partial x_i}-\frac{2}{3}\left[\rho k+\mu_t\frac{\partial(\overline{u_m})}{\partial x_m}\right]\right\} \tag{4}$$

$$\frac{\partial T}{\partial t}+\frac{\partial u_j T}{\partial x_j}=\frac{\partial(-\overline{\grave{u}_j \grave{T}})}{\partial x_j}+\frac{\partial}{\partial x_j}\left(D\frac{\partial T}{\partial x_j}\right) \tag{5}$$

where μ_t is an effective turbulent viscosity (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:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho \overline{u_i} k)}{\partial x_i}=-\overline{\rho \grave{u}_i \grave{u}_j}\frac{\partial(\overline{u_i})}{\partial x_j}-\rho\varepsilon+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \tag{6}$$

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

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho \overline{u_i}\varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}P_k\frac{\varepsilon}{k}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{7}$$

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

$$\varepsilon \sim \frac{k^{\frac{3}{2}}}{L_t} \tag{8}$$

Considering eq. (5), eddy viscosity can be expressed:

$$\mu_t = \rho C_\mu L_t \sqrt{k} = \rho C_\mu \frac{k^2}{\varepsilon} \tag{9}$$

where u_i is the velocity components, ρ – the density of the fluid, $\overline{u_i^{\prime} u_j^{\prime}}$ – the averaged Reynolds velocity stresses, P – the fluid pressure, T – the fluid temperature, D – the thermal diffusivity, $\overline{u_j^{\prime} T^{\prime}}$ – the turbulent heat fluxes, and P_k – the production of turbulence.

The values of the constants are: $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $\sigma_k = 1$, $\sigma_\varepsilon = 1.3$, and $C_\mu = 0.09$.

The solver algorithm which was used was the semi-implicit method for pressure-linked equations (SIMPLE) method, which is used to solve different kinds of fluid-flow and heat transfer problems. It works iteratively with several steps, initially solving the gradients of pressure and velocities, and after that by iterations, it corrects them. The mesh generation of the numerical model was built in GAMBIT, using approximately 60.000 cells, all hexagonal which is presented in fig. 6.

Figure 7 presents the simplified 2-D numerical model of the junction. On the left side, a boundary condition of mass-flow inlet was given to define the flow rate of the Sava River, with its designated temperature. The effluent channel is inclined at around 30° where also mass-flow rate boundary condition was given to define the flow rate, with its designated temperature. On the right side, an outflow boundary condition was given as the mixing water combined and both go the same way, with 100% outflow capacity. The temperature at the outlet is not specified, as the temperature on that spot is our interest to obtain from the simulations. Several sections also were examined, as cross-sections after the junction towards the river outflow, to see the temperature drop as the mixing length increases.

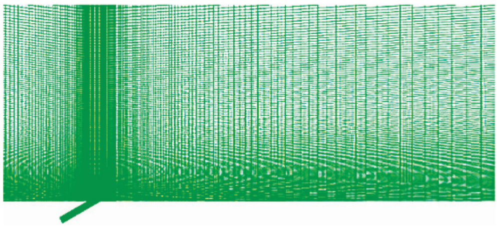

Figure 6. Mesh at the junction and its development

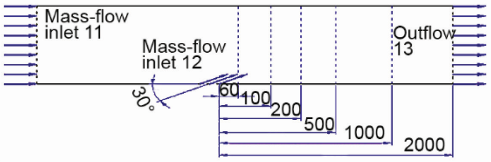

Figure 7. The geometrical characteristics of the channel

The convergence of the results is obtained up to 10^{-8}. Presented results are obtained for atmospheric parameters and power plant operating conditions for the cases of minimum water flow rates in August. The Sava River flow rate was 400 m^3/s, while the effluent flow rate was 40 m^3/s. The average Sava temperature before mixing with effluent water was 23.1 °C.

Results and discussion

The presentation of the temperature distribution was made on several sections through the river bank, at several distances. The temperature values were taken as the average value of those sections. Table 3 presents the results for numerical simulations of thermal pollution in the Sava River for the summer period. The effluent (in the effluent channel) enters the river at a sharp angle (around 30°) concerning the river flow. The contours of temperature are presented in fig. 8.

Table 3. Numerical results

Section [m]	Temperature [°C]
60	31.99
100	31.9
200	31.58
500	30.4
1000	29.3
2000	28.5

Figure 9 shows the comparative results of the EDF method and the numerical analyses. It should be noted that the presented numerical results are for a hot water channel that is placed at an angle of 30° to the direction of the Sava River flow. Temperatures were measured on the surface of the river. The equations of the obtained results show a good matching of the values. Values for distances up to 2 km are shown.

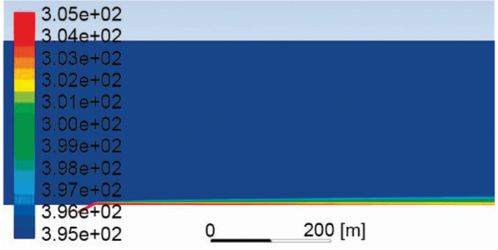

Figure 8. Contours of the temperature of the Sava River

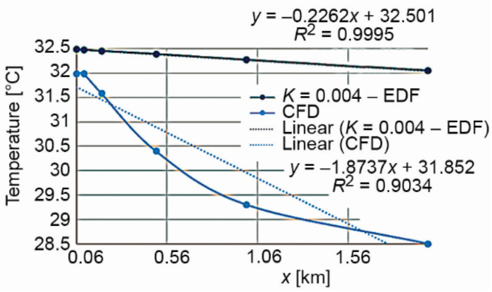

Figure 9. Comparative results of the EDF method and the CFD method

From the diagram, it can be seen that the results were obtained using both methods of lined character. It can be concluded that these results go along. The EDF equation can be modified depending on the exactness of the numerical model, and it can be calibrated to suit the case which was analyzed.

When thermal pollution is analyzed, are being considered near zones and far zones of water mixing. With the analysis made by these methods, it can be established that the results match better in the far water mixing zones. Since the EDF method in its analysis does not use sufficiently precise data on the location of the thermal power plant itself, as well as on the geometric characteristics of the channel, CFD analysis is preferred. The CFD analysis before starting the simulations includes all relevant data of a specific thermal power plant.

Conclusions

In this paper, a comparison of the mathematical EDF method for the analysis of thermal pollution caused by the operation of thermal power plants with numerical simulations was made. During the research, several shortcomings of the application of the mathematical method itself were observed.

The main lack of the EDF method is that the geometry of both the river and the hot water channel was not taken into account, as well as the angle that the hot water channel forms with the river. Depending on this flow, the temperature field at the beginning of mixing differs. In this connection, and based on the diagram, it can be concluded that the EDF method gives better results of the temperature field for larger distances.

Another disadvantage of this method is the lack of a mixing limit temperature. These two waters can mix until the same temperature is reached, after which their temperature field is common. Using the EDF method did not lead to this.

In its model, this method does not treat the flow of either the water of the cooling medium or the hot water channel itself. In that direction, this method should be improved.

Also, it is necessary to form tabular values of the climate factor of certain areas, so that they can be used immediately during calculations without the need to perform a comparative analysis with other results. Such a presentation of this factor would be of great benefit for future designs as well as thermal pollution tests.

Numerical analysis is more complex, gives more precise solutions and it is possible to include different boundary conditions as well as the river flow conditions themselves. However, due to the dependence of numerical analysis on computer time, smaller models are used when forming the network. This is precisely the reason why the numerical analysis was performed only at a distance of 1 km.

At a distance of more than 2 km there would be a matching of the results by the EDF method and numerically. That is, after the complete mixing of the two waters, some constant temperature would be established, which would be close to the initial temperature of the Sava River, before taking part of the flow for the needs of the thermal power plant.

Nomenclature

$C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ – constants
D – thermal diffusivity
K – factor of the climatic area [km^{-1}]
k – turbulence kinetic energy
P – the fluid pressure
P_k – production of turbulence
T – fluid temperature
u_i – the velocity components
$\grave{u}_i \grave{u}_j$ – averaged Reynolds velocity stresses
$\overline{\grave{u}_j \grave{T}}$ – turbulent heat fluxes
x – distance [km]
Δt – river temperature downstream from the hot water outlet from the thermal power plant, [°C]
$\Delta t_{\max}$ – maximum warming of the river caused by hot water discharge, [°C]

Greek symbols

μ_t – effective turbulent viscosity (eddy viscosity)
ε – dissipation rate
ρ – the density of the fluid
σ_k, σ_ε – constants

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