Evaluating the environmental impact of coal-fired power plants through wastewater pollutant vector

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Abstract Reliable and safe operation of a coal-fired power plant is strongly linked to freshwater resources, and environmental problems related to water source and wastewater discharging are challenging the power plant operation. This study deals with an evaluation on basis of wastewater pollutant vector of the environmental impact of residual water generated and discharged in Jiu River during the thermoelectric blocks operation of Rovinari coal-fired power plant. Wastewater pollutant vector Plane Projection is applied for assessing the water temperature evolution in the water flow lane created on downstream from the power plant wastewater outlet channel. Simulation on basis of EDF model and testing validation of EDF Methodology results on thermoelectric blocks of 330 MW of Rovinari power plant are presented in this study.

Keywords Coal-fired power plant, Environmental impact, Pollutant vector, Wastewater

I. INTRODUCTION

Within Industrial Ecology framework, an estimation of the industrial metabolism should explore not only the economic and social benefits, but also the environmental impacts [1,2,3]. The coal-fired power plants represent the larger contributor to acid rain of any industrial activity, since they are the larger source of sulfur oxides. The coal-fired sector is also a significant source of nitrogen oxides, with an impact comparable to that of transportation [4,5,6,7]. Beyond the environmental and human health impacts caused by the air pollutant emissions generated by the coal-fires power plants operation, one could notice also other environmental issues related to water resources and pollutant wastewater generated therein. This study deals with an evaluation on basis of wastewater pollutant vector of the environmental impact of wastewater generated and discharged in Jiu River during the thermoelectric blocks operation of Rovinari coal-fired power plant.

II. WASTEWATER FROM THERMOELECTRIC BLOCKS

Operation. Impacts, Risks and Regulations

Reliable and safe operation of a coal-fired power plant is strongly linked to freshwater resources [8,9,10,11]. Despite the worldwide pressure to retire existing coal-fired power plants and deny permits for new such power plants, as the demand for the electricity is increasing continuously, humankind will not renounce too soon to the fired-coal power plants. But, thermoelectric generation requires a sustainable and large freshwater source, mostly used to cool and condense the steam after it exists the turbine. Further on, thermoelectric blocks operation cause the industrial pollutant wastewater that is discharged in river’s waters.

Due to water availability and quality issues, current and future water-related environmental regulations will challenge the power plant operation [12,13,14].

Currently, on a broader front, the EU Member States face many environmental challenges, still the implementation of European Union legislation should lead to environmental benefits, together with the economic and social ones [12,15]. The benefits of compliance with EU environmental directives and regulations must be addressed meaningfully, together with a shift in human education, both in environmental and economic terms. This way humankind could approach the final step, estimating the value of environmental benefits on basis of people willing and decision, for instance clean drinking water or avoiding illness and cases of premature death caused by the environmental problems [12,13,14,15]. Such environmental challenges could be:

1) Improving and extending the water supply networks to ensure that safe drinking water is available to all settlements.
2) Improving and extending waste water collection and treatment plants.
3) Ensuring that water and air pollutant emissions from thermoelectric power plants are reduced.
4) Cleaning up contaminated rivers and lands where water quality is unacceptable.
5) Protecting eco-systems and habitats from economic pressure.
Addressing such challenges will lead to many environmental and human health benefits, entailing [12]:

a) Reduced risk of water-related illness and improved water taste, as a result of better water quality.

b) Better human health since the exposure to pollutant factor is reduced, and, as result, the number of respiratory diseases and premature deaths will be decreased.

c) Lower consumption of raw materials as a result of cleaner production.

d) Better protection of natural ecosystems for future generations.

Related to water benefits, the compliance should be with the EU Directives and Regulations encompassed by Environmental Acquis (Acquis communautaire) [12,15]:

2. Environmental Information Directive, 90/313/EEC;
4. European Environment Agency Regulation, EEC/1210/90

III. CASE STUDY. WASTEWATER POLLUTION VECTOR OF ROVINARI COAL-FIRED POWER PLANT

Thermoelectric power generation in a coal-fired plant consists in the conversion of thermal energy into electrical energy, on basis of a coal-fossil fuel source to heat a liquid to produce a high pressure gas (usually water is heated to produce steam) which then is expanded over a turbine that runs an electric generator [8,9,16]. The driving force for this process is the phase change of the gas to a liquid following the turbine, and this is where the requirement for cooling water arises. A vacuum is created in the condensation process which draws the gas over the turbine, since this low pressure is critical to the thermodynamic efficiency of the process. Mainly, the water requirement in coal-fired power plants is as cooling water for condensing the steam. The steam condensation typically occurs in a shell-and-tube heat exchanger that is known as a condenser. The operating parameters of the cooling system are critical to the overall power generation yield.

In this study will be analyzed the environmental pollutant vector of wastewaters in Rovinari coal-fired power plant of Romania. The industrial waters supplying the thermoelectric blocks of these power plants are surface waters with a varying temperature in the range 0-30 Celsius degrees. A common trait of the Rovinari, Turceni and Craiova power plants is the same source of supplying water, represented by Jiu River [17]. The pollutant emission source for this river caused by these industrial facilities consists in the wastewater discharging process. Both the supply with fresh water and the discharge of wastewater are performed through the culvert channels provided with special inlets and outlets, respectively. These surface channels are carried out by concrete and embankment (see Fig.1 and Fig.2), with a slope of 1% that ensures a minimum water flow, without destabilizing the optimum level of natural pond.

The water flow supplied by Jiu River to Rovinari Power Plant is provided through the high capacity pumps and by modifying the upstream dam inlet level. The physico-chemical parameters are permanently checked, in real time, through complex equipment installed in a monitoring cabin (Fig.3), with a telemetric transmission of the collected data. This way, in a first stage, there are determined the following fresh water parameters: conductivity, pH, temperature, water level in the channel, water flow rate, inlet water flow. Evaluation of the physico-chemical parameters of fresh water provided through the supplying channel is performed with the measuring transducers. Further on, the water treatment in the Chemical Section (Fig.4) is performed in order to obtain the demineralized water necessary for the steam production, and softened water to be added in the district heating network.

Installation for water pretreatment is necessary for suspension reduction in the raw water, using several decanters operating on basis of coagulation and flocculation processes. Inside the decanters is also performed a decarbonation process, by the
treatment with Ca(OH)$_2$ in order to obtain the precipitation of Ca and Mg soluble salts. Decanted water is stored in tanks, and through a pump system is provided further on towards the demineralized water and softened water installations.

Fig. 4 Water treatment in Rovinari power plant chemical section

Installation for water demineralizing is necessary to produce an appropriate water for steam production. Water demineralizing process is carried out through the six batteries of ionic filters.

Within the water softening installation it is obtained the softened water that is necessary to be added in the district heating network.

A. Discharged Wastewater Pollutant Vector

The thermoelectric blocks of Rovinari power plant are equipped with a water recirculating system using wet cooling towers in order to dissipate the heat from the cooling water to the atmosphere. In this wet recirculating system, the warmed cooling water is pumped from the steam condenser to the atmosphere. In this wet recirculating system, the warmed cooling water is pumped from the steam condenser to the cooling towers [8,9].

The pollutant vector of discharged wastewater ($V_{DWW}$) is completely specified (from a strictly vectorial viewpoint) by: direction, sense, magnitude, origin and tip.

The vector direction is defined by the wastewater discharging channel that links the power plant with the river via an ecological waste water treatment station [18,19]. The vector sense is defined by the wastewater flowing sense. The vector magnitude is related to the wastewater velocity that must be at minimum of 1.5 m/s in order to avoid the suspension sedimentation on the discharging channel bottom. The origin of vector is on power plant inlet site and the tip of vector on the outlet discharging channel.

The physico-chemical parameters of water that can be measured are: temperature, conductivity, particulate matter in suspension, water fixed residue, pH value. Determination of pH value is absolutely compulsory in establishing the acidic or alkaline water. Electrometric measurement is a precise method, and the pH-meter has small dimensions and is mobile. Water acidity is emphasized by the presence of free carbon dioxide, mineral acids and salts of strong acids with weak alkalis. Water alkalinity is highlighted by the presence of alkaline carbonates, bicarbonates, and hydroxides.

B. Wastewater Pollutant Vector Plane Projection

Plane Projection (PP) of wastewater pollutant vector allows the temperature evaluation in the water flow lane created on small distances (up to 500 meters) in Jiu River from the wastewater outlet channel. This is based on the phenomenon of laminar flowing of the pollutant vector of wastewater discharged into a natural environment like Jiu River. On such river areas, the temperature of discharged water determined significant changes that can affect the aquatic fauna and flora.

Plane Projection can be developed for distances smaller than 250 meters. An example of linear temperature distribution if Plane Projection could be developed for distances smaller than 250 meters inside the main isothermal curve. Distribution of isothermal curves (see Table I) if plane projection on distance of 175 meters in the main flowing lane of wastewater pollutant vector is depicted in Fig.5.

C. Projection in Mirror of Wastewater Pollutant Vector

Projection in Mirror (PM) of wastewater pollutant vector allows the temperature evaluation in the water flow lane created on small distances (up to 500 meters) in Jiu River from the wastewater outlet channel. This is based on the phenomenon of laminar flowing of the pollutant vector of wastewater discharged into a natural environment like Jiu River[17,18,19].

The wastewater vector can be equated to a body as symmetrical truncated pyramid pasted to river bank linked to...
discharging water channel. This way, the volume of truncated pyramid body is determined as:

\[ V_a = \frac{m}{3} (L^2 + l^2 + L \cdot l) \]  \hspace{1cm} (2)

On basis of Projection in Mirror the assessment of temperature linear distribution can be developed for distances under 500 meters, within the main isothermal curve. Consequently, the distribution of isothermal curves (see Table II) in the case of PM on distances of 50 meters on wastewater vector (e.g. main isothermal curve) is depicted in Fig.6.

### Table II

<table>
<thead>
<tr>
<th>No.</th>
<th>Isothermal curve</th>
<th>Iso = Isotermal indicative</th>
<th>D_{isom} [m] = distance on isothermal curve</th>
<th>K [°C/m] = longitudinal linearization coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Iso35</td>
<td>35</td>
<td>50</td>
<td>1/50</td>
</tr>
<tr>
<td>2</td>
<td>Iso34</td>
<td>34</td>
<td>50</td>
<td>1/50</td>
</tr>
<tr>
<td>3</td>
<td>Iso33</td>
<td>33</td>
<td>50</td>
<td>1/50</td>
</tr>
<tr>
<td>4</td>
<td>Iso32</td>
<td>32</td>
<td>50</td>
<td>1/50</td>
</tr>
<tr>
<td>5</td>
<td>Iso31</td>
<td>31</td>
<td>50</td>
<td>1/50</td>
</tr>
</tbody>
</table>

\[ \text{Fig.6 Isothermal curves: Iso35, Iso34, Iso33, Iso32, Iso31, Iso30} \]

\[ \Delta t = \Delta t_{\text{max}} \cdot e^{-kx} \]  \hspace{1cm} (3)

where: \( \Delta t \) is the river water residual heating at x kilometers downstream from the warm water outlet; \( \Delta t_{\text{max}} \) is the river water maximum heating after the water mixture in the warm water outlet; k is the climate correction factor, with values ranging between 0.001 and 0.01; x is the distance from the warm water outlet to the river section where the residual temperature is determined.

The mathematic model of temperature evolution in the river water, downstream the warm water outlet through the wastewater pollutant vector allows a reliable evaluation from the errors viewpoint, for river lengths of *10 km, but under 50 km. Numerical simulation is useful in the technical assessment of transient slowly variable processes.

### D. EDF Methodology for Evaluating Wastewater Pollutant Vector

From a designing viewpoint, the discharged wastewater pollutant vector has as flowing frame a river laminar layer, variable from the point of discharging vector outlet. Factors that interfere in calculation of temperatures within the river, downstream the outlet discharge of a warm water flow, are numerous, variable and hard to calculate or measuring. This is the reason for applying over time [8,17,24] an approximate calculus mainly linked on the field measurements. The most simple formula did not take into consideration the temperature evolution downstream the outlet of the wastewater discharging vector, having been concerned only by the mixture of warm water (from the coal-fired power plant) with the river water, that should not exceed a maximum limit.

Assessment of temperature evolution in the downstream outlet river water caused by a warm water discharge is based on a theoretical method that implies some formula entailing exponential factors.

Electricity of France (EDF) Group developed a mathematical model of temperature evolution in river water since a warm water flow had been discharged on downstream outlet, which allows further on reliable numerical simulation:

\[ \Delta t = \Delta t_{\text{max}} \cdot e^{-kx} \]  \hspace{1cm} (3)

...
variable y, denoted by k representing the climate correct factor, with values ranging between 0.001 and 0.01.

The mathematic pattern response to simulation is represented by the multivariable function z denoted by Δt (river water residual heating at x kilometers from warm water outlet discharging).

In the mathematical model it must be emphasized the parameter Δtn representing the maximum heating of river water after the mixture in the warm water outlet.

**F. Testing Validation of EDF Methodology Results on Thermoelectric Blocks of 330 MW of Rovinari Power Plant**

Under the above mentioned conditions, for an acceptable evaluation of the mathematical pattern described by the EDF formula, it is necessary a joint of simulations with experimental tests. For the experimental validation of EDF model, on Jiu River have been performed recordings both for natural thermal load (JIU STN) and for Rovinari thermal load (JIU STR), with the great support of Rovinari Power Plant staff.

Normally, the medium river flow in Rovinari site is roughly 47 m³/s [25]. Operation of 3 thermoelectric blocks in open circuit of Rovinari power plant relies on this river flow, under the environmental parameters stability conditions.

The measurement conditions assume:

1. Maintaining in operation of 3 thermoelectric blocks of 330 MW in Rovinari for 5 hours, 4 hours before measurement and 1 hour during measuring.
2. Positioning human observer with measuring instrument (precision digital thermometer) along the riverbed and into the mainstream of the river, at intervals of 5 km.
3. Establishing the trigger timing of the readings, actually 10 AM, since this is the most appropriate time from viewpoint of heat exchange between Jiu River and environmental surroundings.
4. Performing the 11 temperature readings, over a period of 50 minutes, at intervals of 5 minutes between consecutive readings.
For processing reading data it had been used a AMD multiprocessor computer system that allowed the Microsoft Office - Version 2007 Version 7.0 software running, for data acquisition and processing.

The experimental validation of EDF pattern for wastewater pollutant vector in this case study is emphasized in Table III and Fig.11, which are depicting the data and diagram for temperature \( t \) \([\degree C]\) and distance \( x \) \([\text{km}]\) on River Jiu, for natural thermal load (Jiu River STN) and for Rovinari thermal load (Jiu River STR), respectively.

In Table IV and Fig.12 the isothermal curves Iso31, Iso30, Iso29, Iso28, Iso27 are depicted.

G. Discussion

According to the data depicted in tables and figures as before, one could notice:
- the limit \( x = 7.5 \text{ km} \) for the isothermal curve Iso31= 31\(\degree C\);
- the limit \( x = 20 \text{ km} \) for the isothermal curve Iso30= 30\(\degree C\);
- the limit \( x = 30 \text{ km} \) for the isothermal curve Iso29= 29\(\degree C\);
- the limit \( x = 35 \text{ km} \) for the isothermal curve Iso28= 28\(\degree C\);
- the limit \( x = 40 \text{ km} \) for the isothermal curve Iso27= 27\(\degree C\);

Consequently:

a) For \( k = 0.003 \text{ km}^{-1} \), \( \Delta t_{\text{max}} = 31.5\degree C \), \( n = 3 \), \( P_{\text{inst}}/\text{block} = 330 \text{ MW} \), \( P_{\text{inst}} = 990 \text{ MW} \), the maximum relative error is: \( \varepsilon_{\text{rel}} \leq 5.85\% \);

b) For \( k = 0.004 \text{ km}^{-1} \), \( \Delta t_{\text{max}} = 31.5\degree C \), \( n = 3 \), \( P_{\text{inst}}/\text{block} = 330 \text{ MW} \), \( P_{\text{inst}} = 990 \text{ MW} \), the maximum relative error is: \( \varepsilon_{\text{rel}} \leq 3.66\% \);

c) For \( k = 0.005 \text{ km}^{-1} \), \( \Delta t_{\text{max}} = 31.5\degree C \), \( n = 3 \), \( P_{\text{inst}}/\text{block} = 330 \text{ MW} \), \( P_{\text{inst}} = 990 \text{ MW} \), the maximum relative error is:
\( e_{\text{rel}} \leq 6.51\% \);

d) Optimum of the mathematical model according to relative error, under the conditions \( \Delta_{\text{max}} = 31.5^\circ \text{C}, n = 3, P_{\text{cool}/\text{block}} = 330\text{MW}, P_{\text{cool}} = 990 \text{ MW}, \) it is given by \( k = 0.004 \text{ km}^{-1} \).

IV. CONCLUSION

In technical terms of this case study (Jiu River flow of 47 m/s in Rovinari), the environmental impact of wastewater in opened circuit operation of Rovinari power plant is boundary acceptable.

The EDF mathematical model of temperature evolution within the water of Jiu River downstream the outlet of warm water pollutant vector allows an acceptable evaluation from the errors viewpoint, for river lengths of *10 km, up to 50 km.

For an acceptable evaluation it is necessary a joint of the simulation results (based on EDF mathematical pattern) with experimental tests for wastewater pollutant vector.

Further on, we must have in mind the necessity of assessing overall projections of wastewater pollutant vector, available on both small and large distances.

Another environmental concern is related to abnormal weather conditions, such as arid summer or strong winter frost, when either the electrical capability of the coal-fired power plant would be decreased, either the aquatic ecosystems will be affected by the thermoelectric blocks operation.

ACKNOWLEDGMENT

The authors are highly appreciating the towering support and dedicated efforts of the WSEAS Research Institute in creating a great scientific environment. The authors would like to express their deep and warm gratitude for the professional way in which the WSEAS Research Institute works and understands the scholar concerns and issues. The authors wish also to thank Turceni and Rovinari Power Plants staff for their permanent support in completing this study.

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