Analysis of water management at a closed cooling system of a power plant

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Abstract. The paper presents a mathematical model describing the changes in $\text{SO}_4^{2-}$ ions concentration in a closed system of cooling water circulation in a professional power plant due to the new restrictions posed on industrial emissions by EU and Polish government regulations \cite{1}. Analyzing the behavior of the numerical solutions of the model Authors could determine the optimal volumetric flow rate of wastewater depending on the current configuration of operating power units in a professional power plant.

1. Introduction

In professional power plants, water is commonly used in many industrial processes including, among others: water-steam circulation in power boiler, cooling systems supporting boiler auxiliary equipment (e.g. heat exchangers, compressors) or condensers’ cooling system. Each of these processes requires to ensure appropriate physical and chemical properties of water in order to maintain the continuity of the production of electricity and heat \cite{2}. Due to the fact that daily demand for fresh water in power plants often reaches tens of thousands of m$^3$, these units have to be located near rivers, lakes or other natural reservoirs, where are also released industrial wastewater. Increase production of wastewater and its influence on environment was recently reported e.g. by Blog \cite{3} what indicates on the need for new restrictive regulations for water environment protection. Taking into account its significant impact on natural environment, conventional power plants operated in Poland must satisfy the last industrial waste regulations of The Minister of Environment dated 18 November 2014 and the EU directive \cite{1} which impose, with the beginning of 2016, new limits on the physical and chemical parameters of wastewater released to natural reservoirs. On the other hand, the increase of sewage costs enforces the companies to look for the optimal management of industrial wastes.

Particularly important component of power plant, from the water and wastewater management point of view, is connected with a condenser - cooling tower closed cooling system. Circulating in this system water is heated in the condenser by the condensing steam from the last stage of the turbine, and then cools down in the cooling tower. The main mechanism of the temperature decrease of water inside the cooling tower is connected with a partial evaporation of the flowing water. This phenomenon is associated with an increase of concentration of chemical compounds in the circulating water. This is disadvantageous effect, for instance because an excessive increase in the concentration of sulphate ions $\text{SO}_4^{2-}$ in the water may cause
Corrosion of concrete parts of channels and cooling tower and the increase in the concentration of calcium salts can accelerate the process of their deposition on the exchanges’ surfaces inside the condenser thereby impairing the heat exchange processes [4, 5].

2. Concentration of sulphate ions in cooling system

The scheme of closed cooling water system is presented at figure 1.

![Figure 1. Scheme of closed system of cooling water in power plant](image)

As it was mentioned above, the main mechanism leading to decrease of temperature of circulating water is associated with partial evaporation of the water inside the cooling tower. Due to the fact of continuous evaporation, the total mass of water circulated in the closed system decreases. This leads to the continuous increase of concentration of chemical components in the circulating water. The physical and chemical requirements for cooling water are not as restrictive as in the case of water prepared for steam-water circulation in power boiler, because water does not have a direct contact with boiler or turbine. Despite this, however, the special attention should be paid to its chemical composition, particularly in terms of sulphate (VI) ions. These ions are dangerous because of its corrosive influence on concrete components of the cooling system such as channels or cooling towers reservoirs. Their destructive action on the concrete is connected with \((3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O})\) crystals which precipitate from water in the presence of \(\text{SO}_4^{2-}\) ions. Formation of these crystals in deposits is connected with considerable increase in its volume what may lead to disintegration of the concrete surface.

A simple mechanism leading to decrease of undesirable chemicals concentration in cooling water is associated with periodic discharge of its part to water treatment plants. The missing mass of water is replenished from the natural reservoirs like rivers or lakes. Usually the fresh water has lower concentration of \(\text{SO}_4^{2-}\) ions in comparison to its actual concentration in closed cooling system what causes that the total concentration of \(\text{SO}_4^{2-}\) ions in the closed system decreases. Studies carried out in the professional power plant indicate the monthly changes in concentration of \(\text{SO}_4^{2-}\) ions (denoted by \(x\), [mg/l]). An example results are presented in table 1.

**Table 1.** Mean concentration of sulphate ions \(x\) and mean temperature \(T\) of cooling water during the year

| month | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|-------|---|----|-----|----|---|----|-----|------|----|---|----|-----|
| \(T\), °C | 15,7 | 14,0 | 14,5 | 17,4 | 19,1 | 19,9 | 21,2 | 22,0 | 20,6 | 20,4 | 16,7 | 16,9 |
| \(x\), mg/l | 175,0 | 160,0 | 190,2 | 206,4 | 252,0 | 303,7 | 313,0 | 316,2 | 253,6 | 276,4 | 190,7 | 195,4 |
Presented data indicate that mean monthly concentration of \( \text{SO}_4^{2-} \) ions changes during the year. Two reasons have the significant influence on this situation: high intensity of water evaporation in cooling tower during the summer time and reduction of operation parameters of cooling tower in winter. High ambient temperature during summer in Poland (usually between 20 - 25 \(^\circ\)C) causes that approximate 1% of mass of circulated water evaporates in cooling towers. This intense water loss must be constantly supplemented with natural resources. On the other hand in winter, operators must keep the temperature of cooling water above at the level of 12 \(^\circ\)C due to the technological reasons. Moreover, at this time the intensity of water evaporation is not so high because only a part of the circulating water is cooled down in cooling towers. Monthly changes in intensity of cooling water evaporation are reflected in mean concentration of sulphate (VI) ions. The highest concentration \( \text{SO}_4^{2-} \) is observed in period June-August (more than 300 mg/l), when the lowest concentration is in February (approx. 160 mg/l). Keeping in mind that legal regulations allow on much higher \( \text{SO}_4^{2-} \) ions concentration in waste water (maximally \( x_{\text{lim}} = 500 \) mg/l [1]) it means that operator of the closed cooling system releases more sewage than it is required. This situation gives an opportunity to optimize water management in order to reduce operating costs of the system.

3. Mathematical model

Presented mathematical model enables the prediction of the daily increase in the concentration of sulphate (VI) ions in the closed cooling water system and determines the optimal volumetric flow rate of wastewater due to the current configuration of operating power units in a professional power plant. Balancing the \( \text{SO}_4^{2-} \) ions concentration changes in the cooling system the following processes are taking into account:

- evaporation of water in cooling towers, \( q_{v,ct} \),
- discharge of waste water to the sewage treatment plant, \( q_{v,dw} \),
- replenish of fresh water, \( q_{v,fw} \).

Assuming that the total volume of water in the closed system \( V \) is constant, the change of the current \( \text{SO}_4^{2-} \) ions concentration \( x(t) \) with time \( t \) is described by the differential equation (where \( x_{ct} \) - \( \text{SO}_4^{2-} \) ions concentration in vapour released in cooling tower; \( x_{fw} \) - \( \text{SO}_4^{2-} \) ions concentration in fresh water delivered to the system):

\[
V \cdot \frac{d x(t)}{d t} = -q_{v,dw} \cdot x(t) - q_{v,ct} \cdot x_{ct} + q_{v,fw} \cdot x_{fw}
\]  
(1)

If the total volume of water in the closed system \( V \) is constant, the volumetric flow rates must satisfy balance equation:

\[
q_{v,fw} = q_{v,dw} + q_{v,ct}
\]  
(2)

Expressing volumetric flow rate of evaporated water in cooling towers in (1) by \( q_{v,dw} \) and \( q_{v,fw} \) from (2) one can get:

\[
V \cdot \frac{d x(t)}{d t} = -q_{v,dw} \cdot (x(t) - x_{ct}) + q_{v,fw} \cdot (x_{fw} - x_{ct})
\]  
(3)

Further simplification of (3) is possible if one assumes that \( x_{ct} = 0 \) and \( x_{fw} \) is constant. Then (3) has a form of linear differential equation of first order:

\[
\frac{d x(t)}{d t} + a \cdot x(t) - b = 0
\]  
(4)
where: \(a = q_{v,dw}/V\) and \(b = q_{v,fw} \cdot x_{fw}/V\). Analytical solution of (4) has a form:

\[
x(t) = \frac{b}{a} + \left( x_0 - \frac{b}{a} \right) \cdot e^{-at}
\]

where \(x_0\) refers to initial \(\text{SO}_4^{2-}\) ions concentration in the closed system.

The \(\text{SO}_4^{2-}\) ions concentration in fresh water varies between 40 - 60 mg/l. Then in the model Authors used \(x_{fw} = 60\) mg/l. Figure 2 presents an example of solutions obtained for \(q_{v,cl} = 48000\) m\(^3\)/d and total volume of the circulating water equals \(V = 76750\) m\(^3\).

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Example of analytical solutions of (4) for different initial conditions: A - \(x_0 = 600\) mg/l and \(q_{v,dw} = 10000\) m\(^3\)/d; B - \(x_0 = 60\) mg/l, \(q_{v,dw} = 5000\) m\(^3\)/d

Analyzing presented at figure 2 solutions one can note that in case A the volumetric flow rate \(q_{v,dw}\) is relatively large and causes that sulphate ions concentration in closed system \(x(t)\) decreases when in case B volumetric flow rate \(q_{v,dw}\) is insufficient to prevent an increase in ion concentration with time. From these two examples one can deduce two important conclusions: controlling the volumetric flow rate of discharge of waste water \(q_{v,dw}\) operator can control the actual concentration of \(\text{SO}_4^{2-}\) ions in the closed system and presented functions have asymptotic solutions which depend on initial values of \(a\) and \(b\) parameters. In the presented cases, the asymptotic values of the sulphate ions concentrations are \(x_{asym} = 348\) mg/l and 636 mg/l, for A and B curve respectively.

4. **Water waste management**

Results obtained from the mathematical model have an important influence on water management in power plant. Firstly, it is not possible to reduce a flow rate of waste water too much because it will result in increase of sulphate ions concentration in circulating water. On the other hand, too large waste water discharge will generate increase of financial costs because of the high prices for industrial sewage. It is worth to mention that actual limit for concentration of sulphate ions in waste water (for a cooled surface having a temperature below 60 °C) in Poland is \(x_{limit} = 500\) mg/l. Moreover, the legal regulations are provided for additional penalties for exceeding the permissible concentration limits in sewage. All these aspects cause that power plants must lead a very economical water policy if they want to get the minimum operating costs in this sector.
Analyzing the analytical solution (5) one can determine asymptotic value of $SO_4^{2-}$ ions concentration $x_{asym}$ in circulating water if the constant value of waste water flow rate $q_{v, dw}$ is preserved:

$$x_{asym} = \lim_{t \to \infty} x(t) = \lim_{t \to \infty} \frac{b}{a} + \left( x_0 - \frac{b}{a} \right) e^{-at} = \frac{b}{a}$$  

(6)

If there is assumed that $x_{ct} = 0$ expression $(b/a)$ simplifies to the form:

$$x_{asym} = \frac{b}{a} = \frac{q_{v,fw} \cdot x_{fw}}{q_{v,dw}} = \left( 1 + \frac{q_{v,ct}}{q_{v,dw}} \right) \cdot x_{fw}$$  

(7)

From the formula (7), one can notice that asymptotic value $x_{asym}$ depends only on three parameters: $SO_4^{2-}$ ions concentration in fresh water $x_{fw}$, volumetric flow rate of discharge of waste water $q_{v,dw}$ and volumetric flow rate of evaporated water in cooling tower $q_{v,ct}$. Power plant operator has an influence only on one of them - $q_{v,dw}$ because number of operating cooling towers and weather conditions determine $q_{v,ct}$. Also chemical parameters of fresh water (among them $x_{fw}$) are rather fixed. Asymptotic value $x_{asym}$ can reach level of $SO_4^{2-}$ ions concentration available at fresh water $x_{fw}$ if volumetric flow rate of waste water tends to infinity. From waste water management point of view this solution is costly and thus less economical for power plant. On the other hand there are no operating reasons to maintain the $SO_4^{2-}$ ions concentration as low. Example values of asymptotic ions concentrations $x_{asym}$ for fixed value of $q_{v,ct} = 48000$ m$^3$/d are presented in table 2.

Table 2. Example values of asymptotic ion concentrations $x_{asym}$ for selected values of volumetric flow rates $q_{v,dw}$ and $SO_4^{2-}$ ions concentrations in fresh water $x_{fw}$ (for $q_{v,ct} = 48000$ m$^3$/d)

| $SO_4^{2-}$ ions concentration $x_{fw}$, [mg/l] | 40 | 45 | 50 | 55 | 60 |
|-----------------------------------------------|----|----|----|----|----|
| flow rate $q_{v,dw}$[m$^3$/d] |                |    |    |    |    |
| 5000  | 424 | 477 | 530 | 583 | 636 |
| 7500  | 296 | 333 | 370 | 407 | 444 |
| 10000 | 232 | 261 | 290 | 319 | 348 |
| 12500 | 194 | 218 | 242 | 266 | 290 |
| 15000 | 168 | 189 | 210 | 231 | 252 |

Analyzing data from table 2 one can notice that there exists pairs of $q_{v,dw}$ and $x_{fw}$ for which asymptotic value of $x_{asym}$ is below legally acceptable limit $x_{limit} = 500$ mg/l. It is worth to mention that value of $q_{v,ct}$ is determined by operating parameters of cooling towers as well as its amount and configuration in closed cooling water system.

On the other hand one can use the mathematical model to determine the minimum volumetric flow rate of discharge waste water $q_{v,dw}$ requires to satisfy the legal requirements for $SO_4^{2-}$ ions concentration in waste water releases to natural water reservoirs. If in formula (7) asymptotic ions concentration $x_{asym}$ will be replaced by $x_{limit}$ then one can transform (7) in order to obtain the formula for minimum volumetric flow rate of discharge waste water $q_{v,dw}$:

$$q_{v,dw} = \frac{q_{v,ct} \cdot x_{fw}}{x_{limit} - x_{fw}}$$  

(8)

Assuming that $SO_4^{2-}$ ions concentration in fresh water $x_{fw}$ is fixed as well as volumetric flow rate of evaporated water in cooling towers $q_{v,ct}$ for given number of working cooling tower, an operator responsible for waste water management can calculate for (8) the minimum volumetric flow rate of
waste water $q_{v,\text{dw}}$. Example values of minimal volumetric flow rates $q_{v,\text{dw}}$, parameterized by sulphate (VI) ions concentration in fresh water $x_{fw}$ and volumetric flow rate $q_{v,ct}$, for fixed $x_{\text{limit}} = 500 \text{ mg/l}$ are presented in table 3.

**Table 3.** Example values of minimal volumetric flow rates $q_{v,\text{dw}}$ parameterized by sulphate ion concentration in fresh water $x_{fw}$ and volumetric flow rate $q_{v,ct}$ for fixed $x_{\text{limit}} = 500 \text{ mg/l}$

| sulphate ion concentration $x_{fw}$ [mg/l] | 40     | 45     | 50     | 55     | 60     |
|-------------------------------------------|--------|--------|--------|--------|--------|
| volumetric flow rate $q_{v,ct}$ [m$^3$/d] |        |        |        |        |        |
| 9600                                      | 835    | 949    | 1067   | 1187   | 1309   |
| 19200                                     | 1670   | 1899   | 2133   | 2373   | 2618   |
| 28800                                     | 2504   | 2848   | 3200   | 3560   | 3927   |
| 38400                                     | 3339   | 3798   | 4267   | 4746   | 5236   |
| 48000                                     | 4174   | 4747   | 5333   | 5933   | 6545   |

Keeping the minimal volumetric flow rate $q_{v,\text{dw}}$ which preserves legal regulations for $\text{SO}_4^{2-}$ ions concentration in waste water operator can minimize operating costs of closed cooling water system both saving fresh water resources as well as minimizing the costs for industrial waste water. Presented mathematical model allows not only estimate the minimal requirements for water management in closed cooling water system but also can be useful for testing different waste water strategies. As an example of such possibilities, figure 3 presents two different approaches to the problem of waste water management during the period of 52 days.

![Figure 3](image)

**Figure 3.** Example of the numerical calculations presented different solutions of the mathematical model (1) with initial condition $x_0 = 60 \text{ mg/l}$ and $q_{v,ct} = 48000 \text{ m}^3/\text{d}$. Red curve: $q_{v,\text{dw}} = 6545 \text{ m}^3/\text{d}$; blue curve: $q_{v,\text{dw}} = 5000 \text{ m}^3/\text{d}$ and $10000 \text{ m}^3/\text{d}$ respectively.
Both curves (red and blue one) are calculated for the same initial condition $x_0 = 60$ mg/l and fixed volumetric flow rate of evaporated water in cooling towers $q_{v,ct} = 48000$ m$^3$/d. In case of first solution (red curve) the volumetric flow rate of waste water is fixed during the whole period of 52 days at the level of $q_{v,dw} = 6545$ m$^3$/d (according to the table 3). The blue curve consists of two solutions calculated for $q_{v,dw} = 5000$ m$^3$/d (first 22 days and period between 42 and 52 day) and 10000 m$^3$/d (period between 22 and 42 day). Changes in volumetric flow rate $q_{v,dw}$ for blue curve are forced by legal limit of sulphate (VI) ions concentration $x_{\text{limit}} = 500$ mg/l. Operator have to increase initial value of the volumetric flow rate of waste water up to $q_{v,dw} = 10000$ m$^3$/d in order to avoid exceeding of the legal limit $x_{\text{limit}}$. When the ion concentration decreases to approx. 350 mg/l, operator again reduces volumetric flow rate of waste water to $q_{v,dw} = 5000$ m$^3$/d. So the waste water management works in the cycle of 30 days with ion concentration between 350 and 500 mg/l and $q_{v,dw}$ between 5000 and 10000 m$^3$/d.

Both presented curves preserve legal limits but in first case operator released only 340340 m$^3$ of waste water during 52 days when in the other case 360000 m$^3$. The difference between these two approaches is 19660 m$^3$. It means that optimal waste water management uses approx. 5.8% less fresh water than in second case.

5. Conclusions

Presented mathematical model of changes of SO$_4^{2-}$ ions concentration in closed cooling water system shows possibility of optimization of waste water management under different operating conditions of cooling towers. Basing on information about chemical parameters of fresh water and flow rate of evaporated water inside cooling towers one can estimate the minimum flow rate of waste water in order to preserve legal requirements. This knowledge helps operators and decision makers to lead a planned and cost-effective waste water management in power plants.

References

[1] Council Directive 91/271 / EEC of 21 May 1991. Urban Waste Water Treatment (Acts. Office. EC L 135, 05.30.1991, p. 40, as amended. d.; Acts. Office. Polish special edition, ch. 15, v. 2, p. 26), the Directive of the European Parliament and of the Council 2010/75/EU of 24 November 2010. on industrial emissions (integrated pollution prevention and control) (recast) (OJ. office . EC L 334, 17.12.2010, p. 17, as amended. d.

[2] Laudyn D., Pawlik M., Strzelecky F., Elektrownie, Wydawnictwo WNT, Warszawa 1997.

[3] Blog, S. F., Message to EPA: Time to Modernize America’s Power Plants - Cooling Systems Included, http://switchboard.nrdc.org/blogs/sfleischli/message_to_epa_it_is_time_to_m.html Last cited 4January, 2016.

[4] Hermanowicz W. et al., Fizyczno – chemiczne badanie wody i ścieków, Wydawnictwo Arkady, Warszawa 2010

[5] Stańda J., Woda do kotłów parowych i obiegów chłodzących siłowni cieplnych, Wydawnictwa WNT, Warszawa 1992, 1999.