Wastewater Management in a Closed Cooling System of Professional Power Plant

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1. Introduction

In conventional and thermal power plants water is widely used in many technological processes including e.g.: water-steam cycle in power boiler, cooling system of power boiler, cooling installations of boiler's auxiliary equipment (Stańda 1999). Each of these processes requires constant access to sources of fresh water with its appropriate physical and chemical properties in order to maintain the continuity of the electricity and heat production (Hermanowicz *et al.* 2010). On the other hand, the power plants also are significant producers of pollutants and wastewater. Meaningful increase of production of wastewater and its influence on environment, recently reported e.g. by Blog (Blog 2016), indicates on the need for new restrictive regulations for water environment protection. Care for the environment results in the last industrial waste regulations of The Polish Ministry of Environment dated 18 November 2014 and the EU directive which imposed, with the beginning of 2016, new limits on the physical and chemical parameters of wastewater released to natural reservoirs (EU directive 2010/75/EU of 24 November 2010 on industrial emissions & regulation of the Polish Ministry of Environment dated 18 November 2014). The increase in environmental responsibility together with high penalties for exceeding allowable wastewater limits enforces the companies to look for the optimal management of industrial wastes. The efficient optimization process always bases on the scientific background

involving mathematical modeling and numerical approach which are more widely used in wastewater management (Skoczko *at al.* 2016).

In the paper, there is presented the mathematical model which allows to predict daily changes of sulphate ions concentration in water circulating in a close cooling system of power plant. According to the last regulations, the acceptable concentration of sulphate ions in wastewater is 500 g/m^3. Due to the fact that daily among of released water from cooling system as wastewater usually reaches the level of a several thousand m^3 its proper management could significantly reduce the cost of the system maintenance (Laudyn *et al.* 1997, Berman 1961).

2. Analysis of sulphate ions' changes in cooling system

A closed cooling system of power unit consists of condensers, cooling towers and connecting them concrete channels. Cold water from a cooling tower is transported to a condenser of power unit where is heated up receiving a latent heat during a spent steam condensation process. Next warm water returns to the cooling tower where is cooled down interacting with an air which is in counter flow motion. Cooling process of the circulating water depends on two mechanisms: its partial evaporation and heat exchange between water and the air. The most intensive evaporation is observed in summer when almost 90% of heat is exchanged through this process. The intensity of this process causes that approximately 1% of the flowing water is evaporated leading to the decrease of water temperature even about 10°C (Berman 1961). Depending on volumetric flow rates through the cooling towers, daily water loss in the system, due to its evaporation, reaches from several up to tens thousand m^3.

The understanding of thermal-flow processes inside the closed cooling system has a fundamental importance in an analysis of SO_4^{2-} concentration changes in circulating water because an increase of chemical components' concentrations in the circulating water is connected with its partial evaporation. Evaporated water is replenished by fresh one but its large demand causes that water delivered to the system cannot undergo through complex chemical treatment but mechanical cleaning only. On the other hand, sulphate ions are natural components of fresh water and its initial concentration depends on physic-chemical parameters of the local industrial water sources.

Continuous evaporation process in cooling towers and delivering of fresh water to closed cooling system causes permanent increase of SO_4^{2-} concentration. This is disadvantageous effect, for instance because an excessive increase in the concentration of SO_4^{2-} in the water may cause corrosion of concrete parts of channels and cooling tower as well as the increase in the concentration of calcium salts what can accelerate the process of their deposition on the exchanges' surfaces inside the condenser thereby impairing the heat exchange processes. In order to prevent an exceeding of the permissible SO_4^{2-} concentration limit, a part of water from the cooling system must be periodically removed to the sewage treatment plant.

3. Mathematical model of sulphate ions' concentration

Considering the changes of sulphate ions concentration in circulating water one has to take into account three main mechanisms mentioned in chapter 2:

- evaporation of water in cooling towers, $q_{v,ct}$,
- discharge of wastewater to a sewage treatment plant, $q_{v,dw}$,
- replenishment of fresh water, $q_{v,fw}$.

Relationship between these three abovementioned processes is presented schematically at fig. 1.

Assuming that the total volume of water in the closed system V is conserved, mass conservation law must be satisfied:

$$q_{v,fw}(t) = q_{v,dw}(t) + q_{v,ct}(t) \tag{1}$$

The analysis of losses and replenishment of water allows to formulate differential equation describing changes of SO_4^{2-} concentration in circulating water (t – time in days):
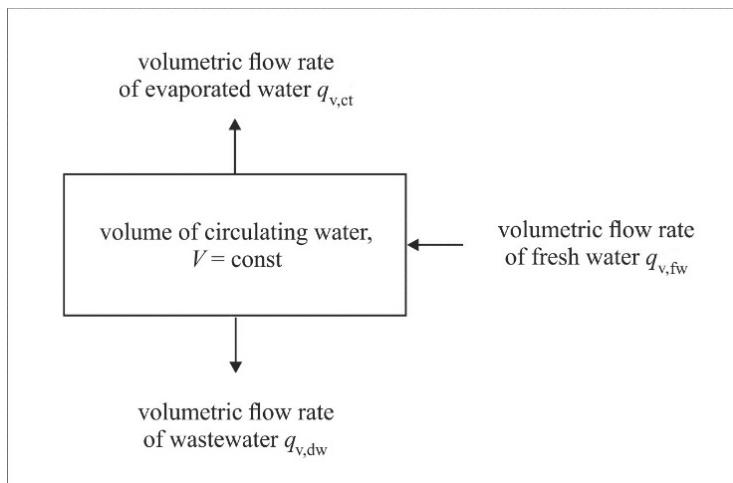
$$V \cdot \frac{dx(t)}{dt} = -q_{v,dw}(t) \cdot x(t) - q_{v,ct}(t) \cdot x_{ct} + q_{v,fw}(t) \cdot x_{fw}(t) \tag{2}$$

where:
$x(t)$ – current concentration of sulphate ions in circulating water,
x_{ct} – sulphate ions concentration in vapor released in cooling tower,
$x_{fw}(t)$ – concentration of sulphate ions in fresh water.

Fig. 1. Schematic balance of water in a closed cooling water system
Rys. 1. Poglądowy bilans wody chłodzącej w zamkniętym układzie chłodzenia

All concentrations are in g/m^3, volumetric flow rates in m^3/d and total volume V in m^3. Equation (2) can be analytically solved if one assumes that:

- volumetric flow rates $q_{v,dw}$ and $q_{v,ct}$ are constant over time,
- sulphate ions' concentration in fresh water is constant over time,
- vapor leaving cooling tower is chemically clean ($x_{ct} = 0$ g/m^3).

Taking into account above mentioned simplifications one can reduce (2) to the form of first order ordinary differential equation:

$$\frac{dx(t)}{dt} = -\alpha \cdot x(t) + \beta \tag{3}$$

where: $\alpha = q_{v,dw}/V$ and $\beta = (q_{v,dw} + q_{v,ct}) \cdot x_{fw}/V$. The solution of (3) is a function which describes change in SO_4^{2-} concentration over time:

$$x(t) = \frac{\beta}{\alpha} + \left(x_0 - \frac{\beta}{\alpha}\right)e^{-\alpha t} \tag{4}$$

where x_0 is an initial SO_4^{2-} concentration in the closed cooling system. On the fig. 2 there are shown two sample solutions of (4) for $q_{v,ct} = 43200$ m^3/d and total water volume $V = 100000$ m^3. Red curve

(case A) shows function (4) for initial sulphate concentration $x_0 = 60$ g/m^3 and volumetric flow of wastewater $q_{v,dw} = 5000$ m^3/d. One can notice that the SO_4^{2-} concentration increases with time up to the level of ~ 580 g/m^3 after 100 days. Blue curve (case B) shows the solution (4) for initial sulphate concentration $x_0 = 600$ g/m^3 and volumetric flow of wastewater $q_{v,dw} = 10000$ m^3/d. In this case the sulphate ions concentration decreases with time reaching approximately 320 g/m^3 after 100 days.
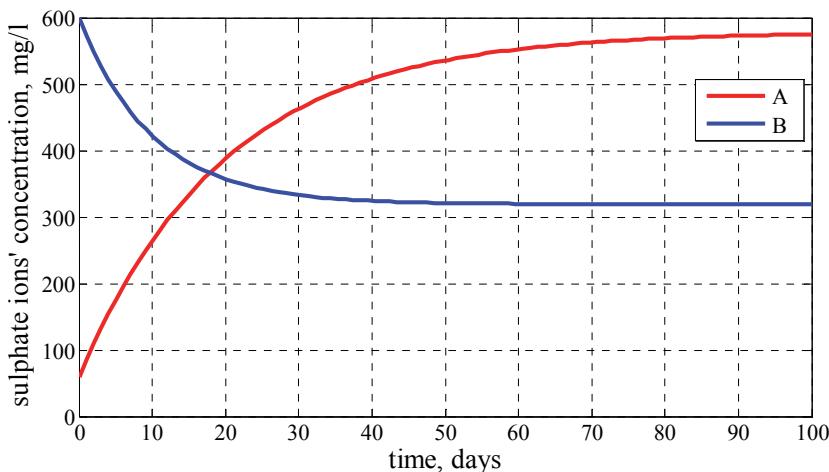
Fig. 2. Sample solutions of (4) for cases:
A (red color) – $x_0 = 60$ g/m^3, $q_{v,dw} = 5000$ m^3/d;
B (blue color) – $x_0 = 600$ g/ m^3, $q_{v,dw} = 10000$ m^3/d
Rys. 2. Przykładowe rozwiązania (4) dla przypadków:
A (czerwony kolor) – $x_0 = 60$ g/m^3, $q_{v,dw} = 5000$ m^3/d;
B (niebieski kolor) – $x_0 = 600$ g/m^3, $q_{v,dw} = 10000$ m^3/d

Figure 2 illustrates two different behaviors of the same function (4) depending on initial state of the closed cooling system. For the fixed value of SO_4^{2-} concentration in fresh water x_{fw}, the final concentration $x(t)$ depends only on the volumetric flow rate of wastewater $q_{v,dw}$. This is very important observation from economical point of view because operator, who controls the level of sulphate ions concentration in circulating water, can optimize the volumetric flow rate of wastewater keeping permissible SO_4^{2-} concentration in closed cooling system. Moreover, A and B curves at fig. 2 illustrate asymptotic behavior of the

function (4). Under given initial conditions, the solution of (3) tends to fixed value denoted by x_{asym}:

$$x_{\text{asym}} = \lim_{t \to \infty} \frac{\beta}{\alpha} + \left(x_0 - \frac{\beta}{\alpha}\right) e^{-\alpha t} = \frac{\beta}{\alpha} \tag{5}$$

The asymptotic value of $x(t)$ is determined by ratio $\beta/\alpha = x_{\text{fw}} \cdot q_{\text{v,fw}}/ q_{\text{v,dw}}$ where $q_{\text{v,fw}}$ is calculated from (1). It is worth to mention that volumetric flow rate through the cooling towers $q_{\text{v,ct}}$ is directly connected with the number of working power units. Having knowledge about current SO_4^{2-} concentration in fresh water x_{fw} and volumetric flow rate of circulating water $q_{\text{v,ct}}$ one can reverse issue asking about minimal volumetric flow rate of wastewater $q_{\text{v,dw}}$ which satisfies legal regulations x_{legal}:

$$x_{\text{legal}} = \frac{x_{fw} \cdot (q_{\text{v,ct}} + q_{\text{v,dw}})}{q_{\text{v,dw}}} \rightarrow q_{\text{v,dw}} = \frac{x_{\text{fw}} \cdot q_{\text{v,ct}}}{\left(x_{\text{legal}} - x_{\text{fw}}\right)} \tag{6}$$

Table 1 presents the example values of minimal volumetric flow rates $q_{\text{v,dw}}$ parametrized by sulphate ions concentration of fresh water x_{fw} and volumetric flow rate of circulating water $q_{\text{v,ct}}$.

Table 1. Example values of minimal volumetric flow rates $q_{\text{v,dw}}$ (in m^3/d), parametrized by sulphate ions concentration of fresh water x_{fw} and volumetric flow rate of circulating water $q_{\text{v,ct}}$, which satisfy legal regulations x_{legal}=500 g/m^3
Tabela 1. Przykładowe wartości minimalnych strumieni objętości odprowadzanych ścieków $q_{\text{v,dw}}$ (w m^3/d) z zamkniętego układu chłodzenia zapewniające spełnienie wymaganego limitu stężenia x_{legal} = 500 g/m^3

SO_4^{2-} ions' concentration x_{fw}, [g/m^3] volumetric flow rate $q_{\text{v,ct}}$, [m^3/d]	40	50	60
28800	2504	3200	3927
36000	3130	4000	4909
43200	3757	4800	5891

Keeping the minimal volumetric flow rate $q_{v,dw}$ which preserves legal regulations for SO_4^{2-} ions' concentration in wastewater operator can minimize operating costs of closed cooling water system both saving fresh water resources as well as minimizing the costs for industrial wastewater.

4. Comparison of the mathematical model with numerical calculation

The mathematical model (2) discussed in chapter 3 has analytical solution (4) under certain significant simplifications like fixed values of volumetric flow rates $q_{v,dw}$ and $q_{v,ct}$ as well as sulphate ions concentration x_{fw} in fresh water over time. It is worth to investigate an influence of variability of $q_{v,dw}$, $q_{v,ct}$ and x_{fw} parameters on a solution $x(t)$. Numerical solution of (2) could be found applying numerical procedure dedicated to solving ordinary differential equation of first order. The equation (2) could be discretized using Euler method with time step Δt (Mathews 1999):

$$x(t_{i+1}) = x(t_i)$$
$$+ \frac{\Delta t}{V}\Big(\big(q_{v,ct}(t_i) + q_{v,dw}(t_i)\big) \cdot x_{fw}(t_i)$$
$$- q_{v,dw}(t_i) \cdot x(t_i)\Big) \quad (7)$$

where $t_{i+1} = t_i + \Delta t$ ($\Delta t = 1$ day). Volumetric flow rate $q_{v,fw}(t)$ is calculated for each time step from the mass conservation law (1). The comparison of analytical solution (4) with numerical data obtained from (7) was derived for fixed values of volumetric flow rates $q_{v,dw}$ and $q_{v,ct}$ as well as sulphate ions concentration x_{fw} in fresh water over time. For better visualization of the agreement of these two curves, figure 3 presents the relative global discretization error e_i calculated from the formula:

$$e_i = \frac{\big(x_a(t_i) - x(t_i)\big)}{x_a(t_i)} \cdot 100\% \quad (8)$$

where: $x_a(t_i)$ and $x(t_i)$ is analytical and numerical solution respectively.

Measurements done on real object indicate that, even if mean values of $q_{v,dw}$, $q_{v,ct}$ and x_{fw} are conserved, its daily values could change

over a dozen percent. This situation is illustrated at fig. 4 for volumetric flow rate of wastewater over a period of 100 days.
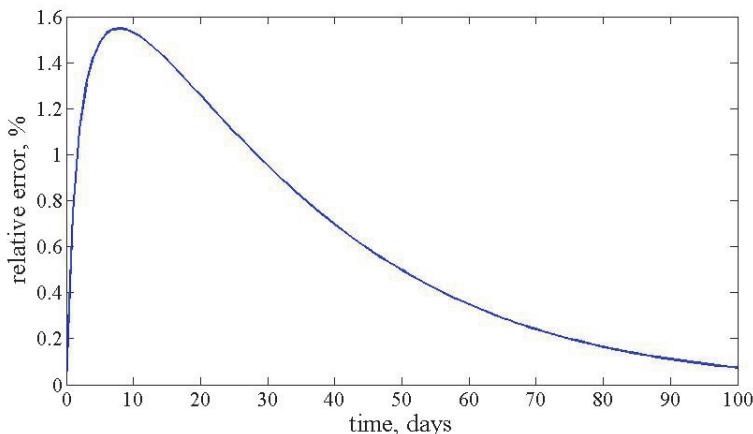
Fig. 3. Relative global discretization error e_i calculated from formula (8) for analytical and numerical solutions obtained for parameters: $x_0 = 60$ g/m^3, $q_{v,dw} = 5000$ m^3/d, $q_{v,ct} = 43200$ m^3/d and $V = 100000$ m^3
Rys. 3. Względny globalny błąd dyskretyzacji e_i obliczony ze wzoru (8) dla analitycznego i numerycznego rozwiązania otrzymanego dla parametrów: $x_0 = 60$ g/m^3, $q_{v,dw} = 5000$ m^3/d, $q_{v,ct} = 43200$ m^3/d oraz $V = 100000$ m^3
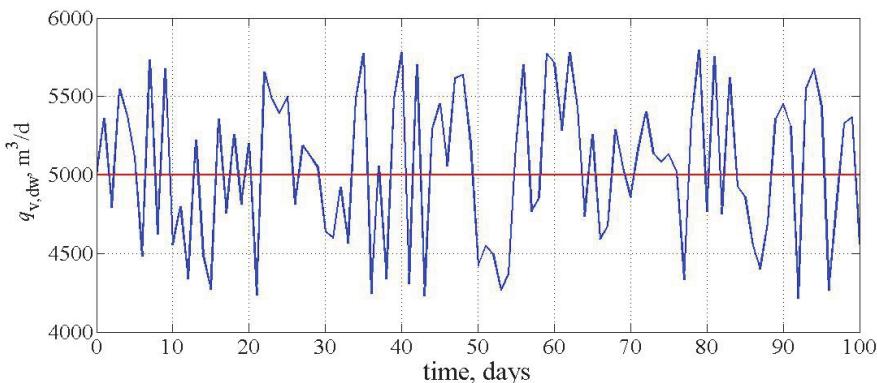
Fig. 4. Fluctuation (blue color) of volumetric flow rate of wastewater around mean value (red color) $q_{v,dw} = 5000$ m^3/d
**Rys. 4.** Fluktuacje strumienia objętości ścieków odprowadzanych z zamkniętego układu chłodzenia (niebieska linia) z zaznaczoną wartością średnią $q_{v,dw} = 5000$ m^3/d (czerwona linia)

In order to obtain more realistic changes of SO_4^{2-} concentration, the time fluctuations of $q_{v,dw}$, $q_{v,ct}$ and x_{fw} parameters were implemented to formula (7). An example of the numerical calculations including time variability of $q_{v,dw}$, $q_{v,ct}$ and x_{fw} is presented at fig. 5 in comparison with smooth analytical solution $x_a(t)$ calculated for mean values of $q_{v,dw}$, $q_{v,ct}$ and x_{fw}. The variability of $q_{v,dw}$, $q_{v,ct}$ and x_{fw} was at the level 20%, 16% and 10% respectively (detailed information is gathered in table 2).

Table 2. Maximum, minimum and mean values of $q_{v,dw}$, $q_{v,ct}$ and x_{fw} parameters noticed in numerical simulation illustrated at fig. 5
Tabela 2. Maksymalne, minimalne oraz średnie wartości parametrów $q_{v,dw}$, $q_{v,ct}$ i x_{fw} uzyskane podczas symulacji numerycznej przedstawionej na rysunku 5

observed value	$q_{v,dw}$, m^3/d	$q_{v,ct}$, m^3/d	x_{fw}, g/m^3
mean	5000	43200	60.0
maximum	5789	47406	71.8
minimum	4210	39008	48.1
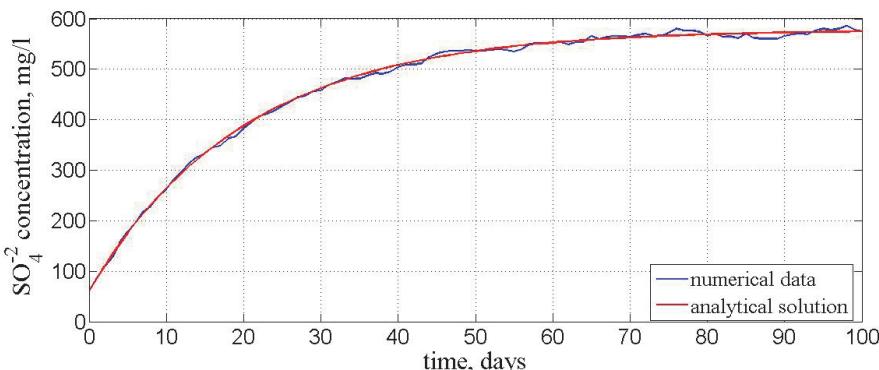


Fig. 5. Comparison of numerical calculation basing on (7) including random fluctuations of $q_{v,dw}$, $q_{v,ct}$ and x_{fw} parameters (blue color) with analytical solution (4) (red color) for the case discussed at fig. 3
Rys. 5. Porównanie rozwiązania numerycznego (7) z losową fluktuacją parametrów $q_{v,dw}$, $q_{v,ct}$ i x_{fw} (niebieski kolor) z rozwiązaniem analitycznym (4) (czerwony kolor) dla przykładu omawianego na rysunku 3

One can notice that numerical data (blue line) oscillate around analytical function (red line) and preserve its asymptotic behavior described by formula (5). The maximum value of relative global discretization error e_i, obtained in the calculation, was 3.2%. Presented example proves that analytical solution of the discussed mathematical model could be used both to optimize the volumetric flow rate of wastewater and fresh water in closed cooling system of power unit.

5. Optimization of wastewater management in closed cooling system

The advantage of the abovementioned mathematical model lies in fast and precise respond on the current working conditions of the cooling system. Using simplified analytical solution with average values of $q_{v,ct}$ and x_{fw} one can estimate optimal flow rate of wastewater $q_{v,dw}$ which preserves legal regulations - $x_{legal} = 500$ g/m^3. An example of the "on-line" modelling of changes of SO$_4{}^{2-}$ ions concentrations is presented at fig. 6. The graph presents a simulation when during first 50 days in a power plant there operated six power units generating the volumetric flow rate of evaporated water through the cooling towers at the level of $q_{v,ct} = 43200$ m^3/d (with $x_{fw} = 50$ g/m^3). Next one of these power units was stopped what caused reduction of $q_{v,ct}$ to the level of 36000 m^3/d. At this situation the actual volumetric flow rate of wastewater $q_{v,dw} = 4800$ m^3/d was too high and the sulphate ions concentration started tend to $x_{asym} = 425$ g/m^3. In order to optimize the costs, after five days, a new volumetric flow rate $q_{v,dw} = 4000$ m^3/d was applied. This corrected let to save 800 m^3 per day during the next 20 days. Finally the power unit returned to the operation and $q_{v,ct}$ increased again to the level of 43200 m^3/d. At this moment the current $q_{v,dw}$ was to low and SO$_4{}^{2-}$ concentration could exceeding the permissible limits. In order to preserve this situation the flow rate of wastewater $q_{v,dw}$ returned to the old level of 4800 m^3/d.
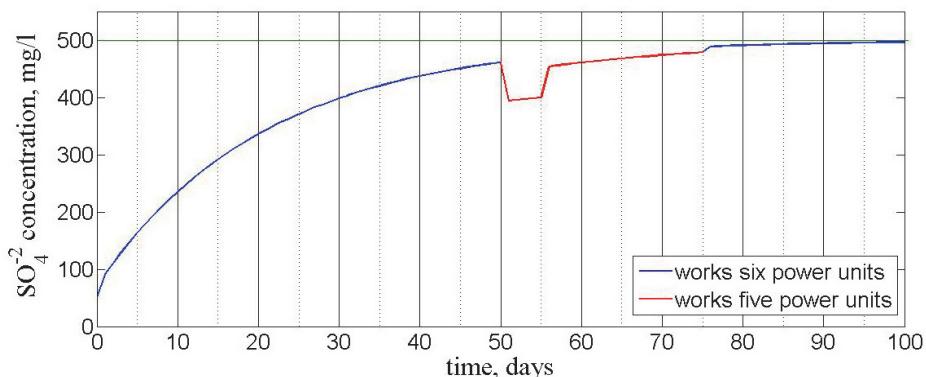
Fig. 6. Simulation of the SO_4^{2-} concentration changes in water under variable number of working power units (red part marks the analyzed period of 25 days)
Rys. 6. Symulacja zmian stężenia jonów SO_4^{2-} w cyrkulującej wodzie przy zmiennej liczbie pracujących bloków (czerwona linia wskazuje analizowany okres 25 dni)

6. Conclusions

Presented in the paper mathematical model allows not only to predict daily changes of SO_4^{2-} concentration in water circulating in closed cooling system but also to indicate asymptotic concentration of sulphate ions under given working parameters of the power system and to calculate minimal volumetric flow rate of wastewater required to keep the SO_4^{2-} concentration below legal regulations. This approach lets on an optimal utilization of water in the system and efficient management of wastewater reducing maintenance costs of the installation.

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Gospodarka wodno-ściekowa w zamkniętym układzie chłodzenia elektrowni

Abstract

The paper presents a mathematical model describing the changes in SO_4^{2-} concentration in a closed system of cooling water in a professional power plant. The analyzed installation consists of condensers and cooling towers connected by a system of channels. The main mechanism of heat transfer in the cooling tower bases on partial evaporation of water, resulting in the increase of concentration of SO_4^{2-} ions in the circulating liquid. The only mechanism to decrease concentration of undesirable chemicals in the circulating water is its periodic discharge to a wastewater treatment. According to the latest Polish Government Regulations (Regulation of the Ministry of Environment dated 18 November 2014) and the Directive of the European Parliament and of the Council (2010/75/EU of 24 November 2010 on industrial emissions) from the beginning of 2016 the new limits on the chemical components of a wastewater led to the natural tanks has been accepted, what forced planned and cost-effective wastewater treatment in a professional power plants. Presented mathematical model has an analytical solution which allows not only to predict daily changes of SO_4^{2-} concentration in circulating water but also to indicate asymptotic concentration of sulphate ions under given working parameters of the system and to calculate minimal volumetric flow rate of wastewater required to keep the SO_4^{2-} concentration below legal value.

Streszczenie

W pracy przedstawiono model matematyczny opisujący zmianę stężenia jonów siarczanowych SO_4^{2-} w zamkniętym obiegu wody chłodzącej bloku energetycznego. Analizowana instalacja obejmuje: skraplacze bloków energetycznych oraz chłodnie kominowe połączone systemem kanałów ssących i kolektorów tłocznych. Głównym mechanizmem wymiany ciepła w chłodni jest częściowe odparowanie przepływającej przez nią wody, co powoduje jednak wzrost stężeń związków chemicznych w cyrkulującej cieczy i wymusza okresowy zrzut części wody do przyzakładowej oczyszczalni ścieków. Zgodnie z najnowszymi rozporządzeniami prawnymi: Rozporządzeniem Ministra Środowiska z dnia 18 listopada 2014 roku oraz dyrektywą Parlamentu Europejskiego i Rady 2010/75/UE z dnia 24 listopada 2010 r. w sprawie emisji przemysłowych, od początku roku 2016 obowiązują nowe limity dotyczące składu chemicznego ścieków technologicznych kierowanych do zbiorników naturalnych, które wymuszają planową i oszczędną gospodarkę wodno-ściekową elektrowni. Prezentowany model matematyczny posiada analityczne rozwiązanie pozwalające nie tylko przewidzieć dobowe zmiany stężeń siarczanów w cyrkulującej wodzie, ale również określić graniczne stężenie jonów siarczanowych dla bieżących parametrów pracy układu oraz wyznaczyć minimalny strumień odprowadzanych ścieków zapewniający spełnienie norm emisji ścieków przemysłowych.