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Mathematical model of sulphate ion concentration in a closed cooling system of a power plant

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ABSTRACT

In commercial power plants, water is used in many processes and its physical and chemical properties have a significant impact on the efficiency of energy and heat production as well as failure-free operation. One of the largest consumers of water in a power unit is the cooling system consisting of condensers and cooling towers. In cooling towers, the main mechanism for the decrease in temperature of the water is its partial evaporation, which causes a gradual decrease in the amount of circulating water and, on the other hand, a continuous increase in the concentration of chemical compounds in the closed system. Among others, an uncontrolled increase in the sulphate ion concentration in cooling water may cause the corrosion of the concrete parts of the hydraulic system as well as an increase in the deposition of calcium salts on the surfaces of the heat exchangers, thereby worsening the heat exchange processes inside the condenser.

The daily demand for fresh water in power plants often reaches tens of thousands of cubic metres and so the amount of wastewater released also has a significant influence on the environment. Therefore the Polish Ministry of Environment and EU directives have introduced, from the beginning of 2016, new limits on the physical and chemical parameters of wastewater released to natural reservoirs. Taking into account the previous regulations, the authors present a mathematical model which allows the prediction of the daily changes of the sulphate ion concentration in the circulating water in a condenser - cooling tower closed cooling system and the calculation of the minimum wastewater flow rate fulfilling legal restrictions.

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1. Introduction

In commercial power plants, water is commonly used in many industrial processes, including, for example, the water-steam cycle in power boilers, the cooling installations in boiler auxiliary equipment or cooling systems operating with condensers [1,2]. Each of these processes requires continuous access to fresh water with suitable physical and chemical properties. Therefore the quality of water has a significant impact on the efficiency of energy and heat production as well as failure-free operation of power units. Taking into account that water is mainly used in heat transfer processes [3], its chemical composition has an influence on the long-term utilization of all kinds of heat exchangers.

It is a well-documented fact that the efficiency of coal-fired power plants gradually decreases with age [4]. It results in the higher emission of the greenhouse gasses as well as other pollutants (which are mainly SO_2 i NO_x). Abovementioned observation applies not only to power boilers but also to internal combustion engines [5–7].

Keeping in mind that the improvement of heat transfer processes could have a direct influence on the overall efficiency of a power unit, Ryabchikov et al. [8] suggested a number of specific actions, among which the retrofit and investigation of cooling water installations are of the most importance.

One of the largest consumers of water in a power unit is the cooling system consisting of condensers and cooling towers. The influence of weather conditions as well as water consumption on the working parameters of cooling towers was recently investigated by Mariano Martín and Mónica Martín [9]. They pointed to the seasonal and climatic impacts on the limitations in the heat

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transfer capacity of cooling systems. Weiliang Wang et al. [10] also investigated the possibility of heat exchange improvement of cooling towers considering the influence of windbreak installations and enclosures on the cooling performance and the flow field characteristics inside cooling towers. The interest in these elements of cooling system design arises from the fact that improving heat transfer inside cooling towers has a direct influence on a better vacuum inside the condensers of the low pressure turbine resulting in an increase in the power unit efficiency.

The main mechanism of the temperature decrease in the water inside cooling towers is its partial evaporation, which causes a gradual decrease in the amount of circulating water and, consequently, a continuous increase in the concentration of chemical compounds in the closed system [11]. Among others, an uncontrolled increase in the sulphate ion concentration in cooling water may cause corrosion in the concrete parts of the channels and cooling towers [12,13] as well as an increase in the deposition of calcium salts on the heat exchanger surfaces, thereby worsening the heat exchange processes inside the condenser.

In order to minimize above-mentioned effects, the circulating water is regularly refreshed, which leads to an increase in the demand for fresh water from natural resources. Having in mind that the daily demand for fresh water in power plants often reaches tens of thousands of cubic metres, the amount of wastewater released from the cooling system also has a significant influence on the environment [14].

In response, the Environmental Protection Agency (EPA) in the USA pointed out that power plants are one of the largest consumers of natural water resources in the USA, recommending, in September 2013, new standards for the control of carbon dioxide (CO_2) emissions from new power units burning fossil fuels and regulations concerning the protection of water resources. It is also worth mentioning that the deterioration of the overall power unit efficiency results in a greater consumption of fossil fuels and consequently higher CO_2 emissions (as well as those of other pollutants) [15]. The Polish Ministry of Environment and EU authorities have also noticed this unfavourable effect and introduced, at the beginning of 2016, new limits on the physical and chemical parameters of wastewater released to natural reservoirs [16]. The cooling system's demand for large amounts of water on the one hand, and the recent legal regulations connected with the chemical parameters of wastewater on the other, mean that power plant operators are forced to introduce optimal methods of water resource management.

Efficient wastewater management needs a scientific background and is based on mathematical models. Focusing on the optimization of fresh water consumption, the authors present an original mathematical model, which allows for the prediction of daily changes of sulphate ion concentration in water circulating in a closed cooling system consisting of condensers and cooling towers.

2. Materials and methods

2.1. Closed cooling system

The closed cooling system is one of the largest fresh water consumers in a power plant. As a result, knowledge about the scientific processes influencing changes in the sulphate ion concentration in the installation is essential for any attempts at establishing a mathematical model. The scheme of a closed cooling water system is presented in Fig. 1.

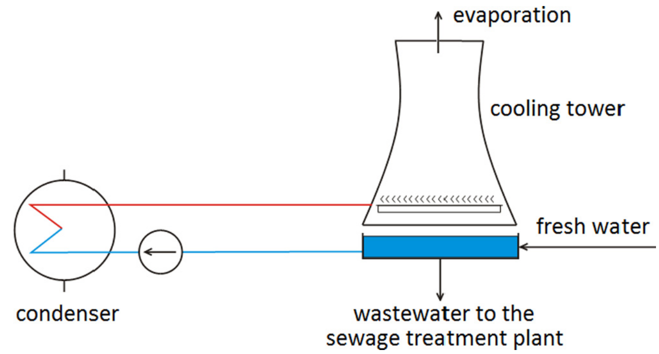

Fig. 1. Scheme of a closed system of cooling water in a power plant.

The water circulating in this system is heated in a condenser by condensing steam from the low pressure turbine, and it is then cooled down in a cooling tower. The main mechanism of water temperature decrease inside the cooling tower is its partial evaporation in contact with counter flowing air [11]. This phenomenon causes a continuous decrease in the mass of the water in the installation and it has a direct influence on the increase of the concentration of chemical compounds (among others, the above-mentioned sulphate (VI) ions) in the circulating water. Due to the fact that the volume of water circulating in the system is usually at the level of hundreds of thousands of cubic metres, it is impossible to apply any chemical methods to reduce the concentration of sulphate ions. Fresh water, before delivery to the closed cooling system, is only mechanically cleaned of solid impurities by means of a set of sieves. So, the only reasonable method of avoiding the uncontrolled increase in the undesirable SO_4^{-2} ion concentration in cooling water, is the periodic discharge of wastewater to a sewage treatment plant. In order to maintain a constant amount of water in the cooling installation, the system is replenished with water from natural resources. This action leads to the reduction of the total concentration of SO_4^{-2} ions in the closed system because the fresh water usually has a lower concentration of sulphate ions in comparison to its actual concentration in the closed cooling system.

Measurements carried out in a commercial power plant indicate seasonal changes in the concentration of SO_4^{-2} ions (denoted by x, [g/m^3]). Sample results are presented in Table 1.

The data presented indicate that the mean monthly concentration of SO_4^{-2} ions changes over the course of the year. There are two significant factors: the high intensity of water evaporation in the cooling tower during the summer and the reduction of the operational parameters of the cooling tower in winter. It is observed, that in summer about 90% of the heat transfer is due to evaporation, which causes approximately 1% of the mass flow rate of circulating water to evaporate in the cooling towers [11]. The intensive evaporation of circulating water is also influenced by weather conditions, mainly through the relative humidity or the orientation and strength of local winds [9,10]. On the other hand, in winter the intensity of water evaporation is limited not only by the low ambient temperature but also for technological reasons. The minimum temperature of the cooling water in the installation is restricted to no less than 11–12 °C. In order to maintain the temperature of the circulating water at above 11 °C in winter only part of it is cooled down in the cooling towers with a subsequent mixing process in the bottom reservoirs between this cooler water and the remaining hotter water.

Analyzing the data from Table 1 it is easy to notice that the intensity of water loss is reflected in the highest value of SO_4^{-2} ion concentration in July and August (up to ~320 g/m^3) in contrast with the lowest concentration in February (approx. 160 g/m^3). Keeping in mind that legal regulations allow for a much higher SO_4^{-2} ion concentration in wastewater (maximally x_{limit} = 500 g/m^3 [16]), the operator of the closed cooling system releases more

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