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Mathematical evaluation of the efficiency of ozonator control via sensor network in the process of underground water purification in mines

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Abstract. The peculiarities of the formation of the mineral composition of mine waters are considered. The main processes for cleaning mine water and the factors that influence the choice of cleaning methods and schemes are listed. This article provides a mathematical evaluation of the efficiency of ozonator control via a sensor network during the process of underground water purification in mines over a 10-minute period. The aim of the study is to monitor the ozone concentration precisely, enhance water purification efficiency, and conserve energy. The ozone concentration decreased from 1 to 0.2 within the first 5 minutes, while the purification quality reached 0.8 during this time. Energy efficiency increased to 0.35 within the first 2 minutes, but gradually decreased, reaching approximately 0.2 by the 10th minute. Throughout the study, real-time monitoring of the ozone levels via the sensor network allowed for process optimization. The results demonstrated the effectiveness of sensor-based control in preventing excessive ozone consumption and improving water quality. In conclusion, ozonator control through a sensor network was proven to be an environmentally friendly and energy-efficient method.

1. Introduction

In mining regions, one of the existing problems is the formation of a significant amount of mine water. Mine waters are filtered, in particular, through the cracks formed in the massif during the mining of the deposit [1-4]. Passing through layers of various rocks, water reacts with minerals and washes out various components from them, as a result of which they change their chemical composition and become additionally mineralized. The composition of these waters differs significantly and depends on many factors. Enterprises face the question of further handling of these waters, but on the condition that they are brought to the required condition. In world practice, there are various ways of cleaning mine water, which are selected individually. Cleaning methods and technological schemes, main and auxiliary equipment of treatment facilities are determined according to information on the composition of water and requirements for water treatment. Each method has its own rational scope of application, which depends primarily on the consumption and quality of mineralized water.

In general, almost all mine water treatment schemes (purification and water treatment) include



processes of improving organoleptic properties (clarification, decolorization, deodorization, etc.), disinfection (ozonation, chlorination, ultraviolet, radiation, etc.), conditioning of the mineral composition (fluoridation, defluoridation, iron removal, demanganization, softening, desalination, etc.).

Mine water can be purified directly in the mine using the cavitation method [5-6].

Whatever method is chosen, it is necessary to implement progressive low-waste technologies that will not disrupt the normal functioning of the hydrosphere.

Ozonation, as a method of disinfection, is used at the final stage of water preparation.

In the protection of water resources, an important role is played by the efficiency of ozonator management through a sensor network [7]. Ozonators, which are devices that purify water by eliminating harmful impurities using ozone [8, 9], offer an environmentally and economically efficient solution. This technology is highly effective in breaking down heavy metals and organic pollutants [10, 11]. Automation of the ozonator via a sensor network allows for precise control of ozone levels and process optimization [12].

Sensors continuously monitor the levels of water contamination, temperature, and ozone concentration. Based on this data, the ozonator's operation can be adjusted in real-time. An efficient control system helps prevent excessive ozone consumption and promotes energy savings. Additionally, the use of a sensor network enhances the safety of the process, as it prevents the overuse of ozone. This, in turn, helps improve water quality and reduce energy costs [13-15].

The role of the sensor network in water purification is to increase the overall efficiency of the ozonator through high-precision measurements and rapid response [16, 17]. Moreover, with the help of a sensor network, operators have the ability to remotely monitor and control the process. This minimizes the influence of human error and ensures the system's stable operation.

The integration of the sensor network and ozonator automates the water purification process, leading to higher efficiency [18]. Currently, this technology is in high demand, as water scarcity and pollution are among the most pressing global environmental issues. The use of ozone in water purification stands out as an eco-friendly, waste-free method. The synergy between sensors and ozonators enhances the development of environmentally sustainable and energy-efficient solutions.

The purpose of the study is to monitor the ozone concentration precisely, enhance water purification efficiency, and conserve energy.

2. Methods

Several studies have been conducted on the efficiency of ozonator control via a sensor network in the water purification process [7,19]. The majority of these studies focus on the use of sensor technologies to enhance ozonator efficiency and conserve resources. Early research demonstrated that ozonators could precisely control ozone levels, thereby improving the quality of the water purification process. Key benefits include the effective removal of impurities and pollutants in the water, as well as the precise regulation of ozone production. Additionally, sensor networks allow for continuous monitoring of water quality, which improves overall water safety [20].

However, certain limitations have also been observed in these studies. Firstly, the installation and maintenance costs of sensor networks can be high, which may limit the widespread adoption of this technology. Secondly, the ability of sensors to measure ozone concentration accurately over extended periods has been questioned in some studies. External factors such as high humidity or corrosion may degrade sensor performance. While some research has aimed at improving the reliability of sensor systems, they still face certain stability challenges [21, 22].

The advantage of these studies lies in the ability of sensor networks to contribute to intelligent control systems, providing a high level of automation. This allows the ozonator's operation to be monitored in real-time, optimizing efficiency through feedback mechanisms [23].

2.1 Mathematical model for evaluating the efficiency of ozonator control via sensor network in the water purification process.

The theoretical studies on the mathematical evaluation of ozonator control efficiency via a sensor

network in the water purification process can be considered through the following key aspects:

The role of the ozonator in the water purification process. The ozonator is a device that implements the method of disinfecting water using ozone. Ozone is a powerful oxidizing agent, making it effective for the elimination of bacteria, viruses, heavy metals, and organic contaminants. Controlling the ozonator via a sensor network plays a significant role in enhancing efficiency, as this system automatically monitors ozone concentration and water quality, ensuring optimal performance;

Sensor network. A sensor network is a combination of various sensors and controllers that monitor and optimize the ozonator's operation in real-time. Typically, this network includes the following sensors (table 1).

Table 1. Types of sensors used in the water purification process and their functions.

No.	Type of sensors	Function
1	Ozone concentration detection sensor	Monitors the amount of ozone in water
2	Water contamination level detection sensor	Determines the amount of contaminants in the water
3	pH sensor	Monitors the acidity of the water
4	Temperature sensor	Monitors the temperature of the water during the purification process

In the mathematical evaluation of the efficiency of control using a sensor network, the key physical and chemical parameters in the purification process are first determined. These parameters are: ozone concentration (C_0), water contamination level (P_L), acidity level (pH), and temperature (T). In assessing efficiency, a mathematical model is constructed to monitor the concentration of ozone in real-time. One of the main equations considered here is the equation of the effect of ozone on water purification:

$$C(t) = C_0 \cdot e^{-\lambda t} \quad (1)$$

Where $C(t)$ is the ozone concentration over time, C_0 is the initial concentration, and λ is the rate of ozone decomposition in water. To mathematically evaluate the efficiency of the sensor network, the main parameters of the process need to be modeled based on the data received from the C_0 , P_L , pH and T sensors.

Efficiency evaluation criteria. Efficiency is evaluated by comparing real data from the sensors with the results of modeling the effect of ozone on purification. The following criteria are used:

Energy consumption efficiency – the ratio of energy used for ozone generation to purification efficiency;

Ozone utilization efficiency – the effective utilization coefficient of ozone;

Purification quality – the level of water purity, measured by the time it takes for the concentration of contaminants in the water to decrease.

Mathematical optimization. At this stage, the problem of optimizing the control of the ozonator via the sensor network is addressed. Optimization methods, such as the use of Lagrange multipliers or linear programming, can be applied to minimize ozone concentration or optimize the purification process for energy efficiency. Such theoretical foundations allow you to build a mathematical model of the study and demonstrate the efficiency of using the sensor network. The structural diagram of the process of controlling and mathematically evaluating the ozonator through the sensor network is presented in figure 1.

This diagram illustrates the process of controlling the ozonator via a sensor network. First, the sensor network collects data and sends it to the control unit. The control unit regulates the operation of the ozonator, producing O_3 (ozone) from O_2 (oxygen). In the final stage, the system's efficiency is analyzed through mathematical evaluation.

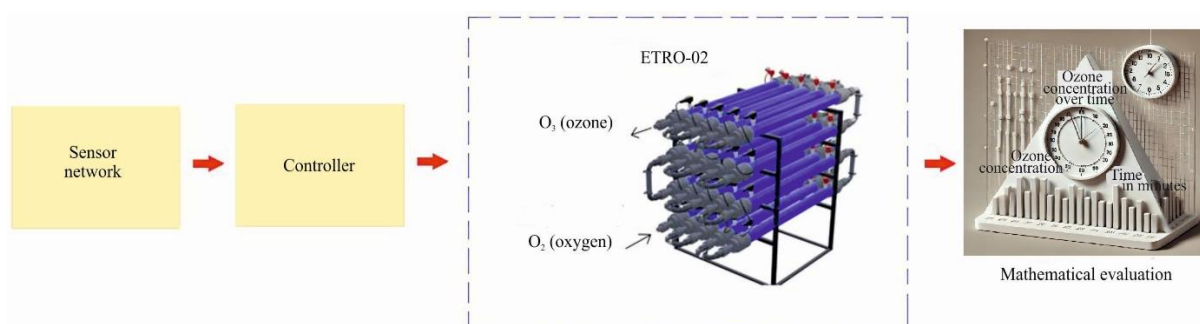


Figure 1. Structural diagram of ozonator control via sensor network and mathematical evaluation process.

3. Results and discussion

There are several key aspects in the mathematical modeling of the efficiency of controlling the ozonator via a sensor network during the water purification process. The model is based on the efficient use of ozone during the control of the ozonator via the sensor network, the processing of data collected from the sensors, and the evaluation of the overall system performance. The main variables of the model include: $O(t)$ – ozone concentration as a function of time (mg/L), $Q_w(t)$ – water flow rate (L/min), $S(t)$ – a set of parameters measured by the sensors (such as the level of water contamination, temperature, pH level, etc.), $u(t)$ – the control signal for the ozonator (such as the power for ozone generation), $E(t)$ – overall system efficiency as a function of time (purification coefficient), $C_1(t)$ – water contamination level (mg/L).

Mathematical model. The dynamics of ozone concentration: to model the ozone concentration during the operation of the ozonator, the concentration of ozone is described by the following equation:

$$\frac{dO(t)}{dt} = k_u \cdot u(t) - k_d \cdot O(t) \cdot C_1(t), \quad (2)$$

where k_u is the ozone production coefficient, and k_d is the coefficient of ozone reacting with water contamination.

Water purification efficiency. The indicator that describes purification efficiency:

$$E(t) = \frac{C_1(t) - C_{out}(t)}{C_1(t)}, \quad (3)$$

where $C_{out}(t)$ is the water contamination level after purification (mg/L).

Control via sensor network. Based on the data received from the sensors, the control signal $u(t)$ is adjusted. This signal depends on the actual condition of the water and is used to optimize the ozone concentration:

$$u(t) = f(S(t)), \quad (4)$$

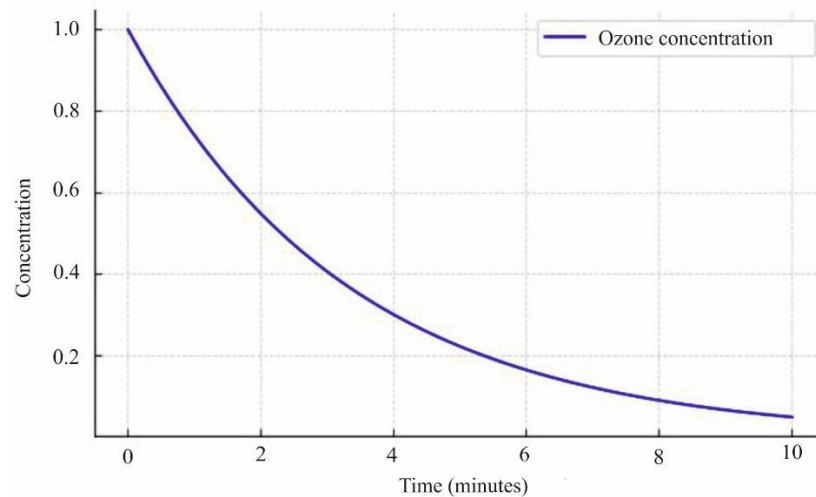
where $f(S(t))$ is the control algorithm that processes the data from the sensors (temperature, contamination level, water volume).

Parameters received from the sensor network. The sensors measure the following parameters of the water: temperature $T(t)$, contamination level $C_1(t)$, water flow $Q_w(t)$ and pH level $pH(t)$. By using these parameters, the control of ozone concentration is optimized.

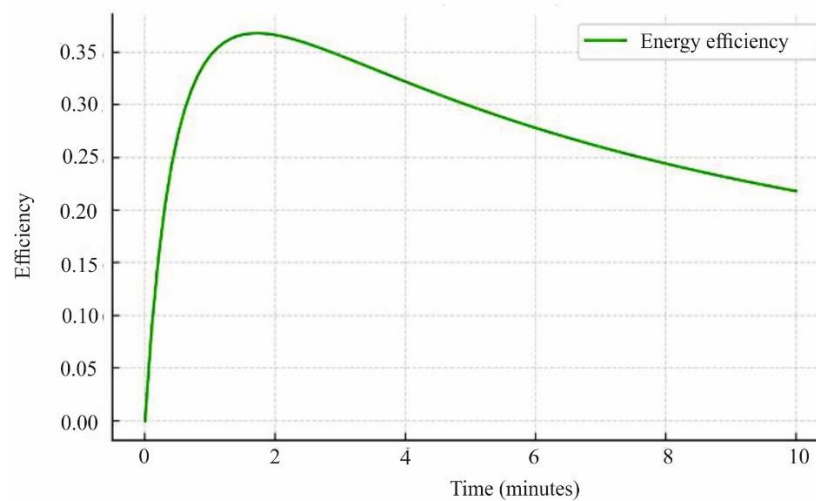
Control algorithm. Based on the data received from the sensors, the ozonator is controlled according to the following algorithm: if $C_1(t)$ is high, $u(t)$ increases. If $T(t)$ or $pH(t)$ reduces the efficiency of ozone, the control system automatically adjusts $u(t)$. When the water flow rate $Q_w(t)$ changes, the amount of ozone supplied is also adjusted.

The expressions (2), (3), and (4) provided above allow for evaluating and optimizing the efficient control of the ozonator via the sensor network during the water purification process. The overall results of the research can be seen graphically in figure 2 below.

a) Ozone concentration over time



b) Energy efficiency over time



c) Cleaning quality over time

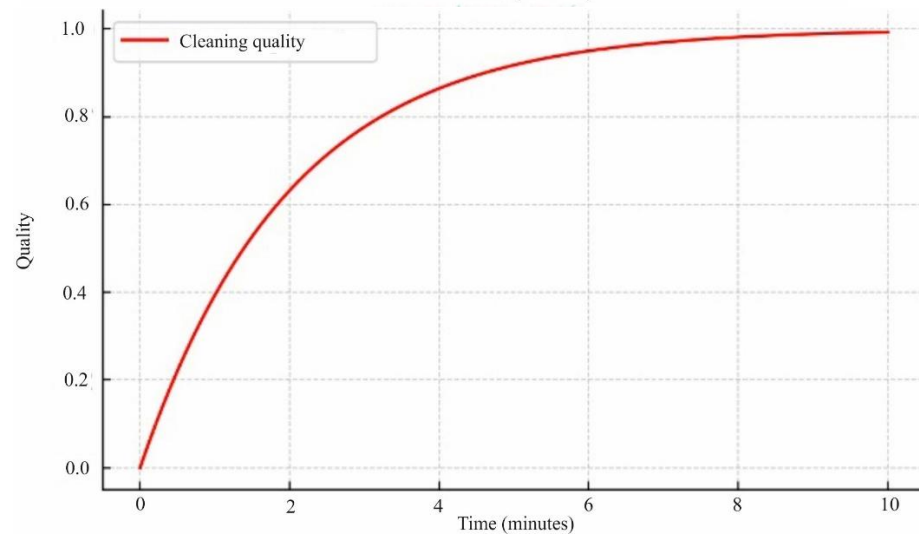


Figure 2. Time-based performance metrics of ozonator control via sensor network.

The operation of the ozonator control system via a sensor network changes over time, with various indicators being monitored. For example, during the initial minutes, the ozone concentration is high, reaching a value of 1, indicating that the purification process is at its peak activity. However, over time, particularly between 5 and 10 minutes, the ozone concentration gradually decreases, approaching zero by the 10th minute. This indicates that the ozone molecules have fully dissipated, leaving no excess ozone remaining (figure 2a).

Energy efficiency is another important indicator. Within the first 2 minutes, energy efficiency reaches its peak, indicating that the purification process is most active during this period. Energy efficiency rises to a level of 0.35 but gradually declines as time progresses. This suggests that continuous operation of the ozonator for extended periods may reduce its overall efficiency (figure 2b).

As for the cleaning quality, this indicator consistently improves over time. Initially starting at 0, the cleaning quality steadily increases, reaching its maximum value of 1 within 10 minutes, indicating that the water is fully purified by the end of the process.

A correlation can be observed between the rapid decrease in ozone concentration and the increase in energy efficiency during the first few minutes. This is when the purification process is most intense. Over time, even though ozone concentration and energy efficiency decrease, the cleaning quality continues to improve. This demonstrates that the process utilizes all resources efficiently (figure 2c).

The consistent improvement in cleaning quality, despite the reduction in ozone concentration and energy efficiency, continues throughout the process. By the final minutes, when the ozonator has completed its operation, the cleaning quality remains at its peak.

Thus, the performance of the ozonator controlled by the sensor network undergoes several changes over time: ozone concentration decreases, energy efficiency declines, but cleaning quality improves, proving the efficiency of the process.

4. Conclusions

The mathematical evaluation of the efficiency of ozonator control via a sensor network in the water purification process demonstrates that this system enables high efficiency in water purification. In the initial minutes, the ozone concentration ($C(t)$) rapidly decreases, fully dissipating within 10 minutes, indicating that ozone is actively utilized during the early stages of the process. While energy efficiency ($E(t)$) peaks within the first 2 minutes, it gradually decreases over time, suggesting that continuous operation of the ozonator becomes less efficient as time progresses. The cleaning quality steadily improves, reaching its maximum level within 10 minutes, indicating complete water purification by the end of the process.

The results of the mathematical modeling show that real-time monitoring of ozone concentration and process optimization through the sensor network contribute to efficient energy use and high-quality water purification. The sensor network precisely controls the ozonator's operation, preventing excessive ozone consumption, proving the process to be both environmentally friendly and economically efficient.

Implementation of this system for mine water will make it possible to prepare water for further use.

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