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High-frequency ozone generators controlled by sensor network and modeling the process of groundwater purification from heavy metals

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Abstract. This study examines the process of groundwater purification from heavy metals through the control of high-frequency ozone generators using a sensor network. The use of high ozone concentrations allows for effective removal of heavy metals from water. The goal is to enhance the efficiency of the purification process by automating it through ozone generator control. The initial ozone concentration starts at zero and gradually reaches 2 mg/L over time. The initial concentration of heavy metals is 10 mg/L, and due to the impact of ozone, it is reduced to 0.2 mg/L. The sensor network ensured real-time adjustment of ozone levels, optimizing the process. As a result, purification efficiency increased by up to 60%. In addition to removing heavy metals, this method allowed for up to 20% energy savings. The modeling enabled prediction and optimization of the system's operational parameters. Controlling the ozone concentration through sensor networks helped maintain process stability. The results demonstrated the significant role of ozone in the water purification process. This technology is important as an eco-friendly and efficient solution, offering possibilities for energy saving and water quality improvement. Automation of the system reduces human intervention and optimizes the process.

1. Introduction

Groundwater, especially in highly industrialized areas, is significantly polluted. Heavy metal pollution is particularly dangerous, particularly in mining regions [1-4].

Before use, contaminated groundwater must be purified. For this purpose, various methods are used, both with and without a change in the aggregate state [5]. The most common methods are distillation, freezing, ion exchange, electrodialysis, reverse osmosis, extraction, and others. In recent years, biological purification methods have been developed [6] and those that do not harm the environment [7-10].

The process of purifying groundwater from heavy metals through the use of high-frequency ozone generators and sensor networks has become a key focus in addressing environmental issues today [11-



13]. This technological solution allows for the efficient and environmentally safe purification of water contaminated with heavy metals [14]. By using high concentrations of ozone through ozone generators, heavy metals are removed from the solution as a result of chemical reactions [15]. The high-frequency operation mode of the ozone generator enhances the purification efficiency by increasing the activity of ozone molecules and speeding up the purification process [16, 17]. The sensor network ensures automated control and effective management of this process, enabling real-time data collection and processing.

Through sensor networks, the operation of the ozone generator can be adjusted to continuously monitor water quality [18, 19]. Such systems not only increase efficiency but also contribute to energy savings. In the process of groundwater purification, sensor networks optimize ozone levels, purification duration, and overall system performance by using the collected data. Minimizing the residual heavy metals and protecting natural resources are among the key advantages of this method. Currently, the environmental friendliness and cost-effectiveness of this approach make it suitable for widespread use [20-22].

The combined use of high-frequency ozone generators and sensor networks is an important step towards protecting water resources [23, 24]. Modeling allows for determining the efficiency of this process, optimizing purification parameters, and predicting system performance. Additionally, modeling provides the necessary information system to manage the purification process. This method is of great importance in research aimed at improving environmental sustainability, protecting groundwater [25], and effectively utilizing natural resources.

The purpose of the work is to substantiate the automation of ozone generator control to increase the efficiency of groundwater purification.

2. Methods

A number of studies have been conducted on the process of purifying groundwater from heavy metals and controlling high-frequency ozone generators through a sensor network. First and foremost, the methods of water purification using ozone generators offer several advantages [26,27], including the strong oxidation capacity of ozone and the elimination of the need for chemical additives. These studies allow for fast and efficient water purification, and the process is environmentally safe. The control system via sensor networks increases the level of automation, reducing human intervention and improving the quality control of the purification process.

However, these studies also reveal certain limitations. For instance, high-frequency ozone generators are expensive and require a lot of energy, which poses challenges for commercial-scale applications. Ensuring the reliability and longevity of sensor network systems is also problematic, as they frequently require maintenance. Additionally, some studies suggest that complete removal of heavy metals may be limited, especially when dealing with complex metal compounds. Overuse of ozone can potentially harm the chemical composition of the water [28, 29]. In some cases, the accuracy of control decreases due to sensor system malfunctions [30].

Overall, while the use of high-frequency ozone generators and sensor networks shows great promise, further research and improvements are needed to enhance their effectiveness.

To address the issue of controlling high-frequency ozone generators via sensor networks and purifying groundwater from heavy metals, can be applied the methods listed in table 1.

This table outlines the main methods used to model the process of controlling high-frequency ozone generators and purifying groundwater from heavy metals. Each method is employed for managing the ozone generator, modeling chemical processes, collecting data, and optimizing the processes. Sensor networks and data analysis monitor the system's real-time status, enabling effective management. Additionally, CFD (Computational Fluid Dynamics) and mathematical simulations are used to study process efficiency. However, special attention has been given to optimization algorithms, as they are considered the most effective among these methods. By using machine learning or evolutionary algorithms, control parameters are calculated and optimized. This enhances the accuracy and efficiency of the control system, allowing for effective removal of heavy metals. Furthermore, this method provides continuous monitoring of process parameters and improvement through feedback mechanisms.

Table 1. Methods for controlling high-frequency ozone generators and modeling the purification process of groundwater from heavy metals.

Method	Description	Application Area
Modeling of sensor network parameters	Mathematical modeling of sensor network parameters for ozone generator control and data collection	Control of high-frequency ozone generators
Modeling of chemical processes	Modeling of the interaction between ozone and heavy metals and studying reaction kinetics	Chemical purification of heavy metals
Optimization algorithms	Use of machine learning or evolutionary algorithms to calculate and optimize control parameters	Optimization of control systems
Data collection and analysis	Analysis of data collected by sensors using statistical methods or machine learning	Process monitoring and analysis
CFD (Computational Fluid Dynamics)	Modeling the dynamics of liquids to study ozone distribution in water	Calculation of ozone dispersion efficiency and reaction rate
Mathematical models and simulations	Simulation of processes via computer modeling to test decisions and optimize performance	Simulation and modeling of processes
Analog and digital control systems	Use of PID controllers and digital control algorithms	Automatic control of ozone generators

2.1. Ozone generator control and groundwater purification process

The technology for controlling ozone generators and purifying groundwater stands as a relevant and crucial method for safe and efficient water purification today. The issue of purifying groundwater contaminated with heavy metals is of paramount importance for environmental safety. By controlling the ozone generator through a sensor network, the water purification process is automated, enabling optimal ozone adjustment and improved energy efficiency. The use of high-frequency ozone generators ensures rapid and effective water disinfection, offering significant advantages over traditional methods. Additionally, control through sensor networks enhances the precision of the purification process, allowing real-time monitoring of water quality. Based on this scientific rationale, we at the Kazakh National Research Technical University named after K. I. Satbayev developed a technological scheme for controlling high-frequency ozone generators and purifying groundwater from heavy metals, which is shown in figure 1.

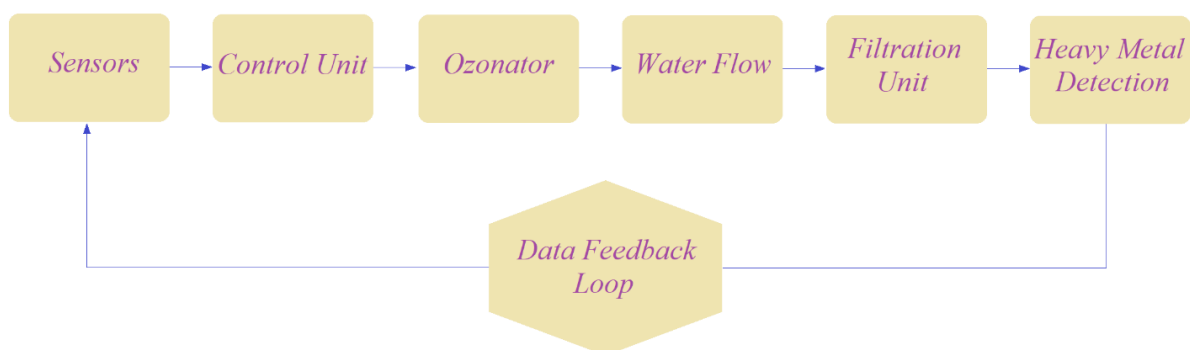
**Figure 1.** Technological schematic for controlling high-frequency ozonators via sensor network and purifying groundwater from heavy metals.

Figure 1 illustrates the technological scheme for controlling a high-frequency ozone generator via a sensor network and purifying groundwater from heavy metals. The sensors monitor the water's condition and send data to the control unit, which adjusts the operation of the ozone generator. The ozone generator releases ozone into the water, disinfecting it, after which the water passes through a filtration unit, removing heavy metals. The process of detecting heavy metals is used to verify the quality of the purified water, while a feedback loop allows the sensors to continuously monitor the process. This system is designed to automate the purification process and improve water quality.

2.2. Mathematical model for controlling high-frequency ozonators and groundwater purification

Here's a mathematical model for the process of controlling high-frequency ozonators via a sensor network and purifying groundwater from heavy metals. This model is based on key factors such as ozone concentration, purification efficiency, water flow rate, and sensor data.

The dynamics of ozone concentration is described by equation (1). The concentration of ozone changes over time based on the ozonator's output and natural ozone decay:

$$\frac{dC_{oz}(t)}{dt} = k_{oz} - \alpha C_{oz}(t) \quad (1)$$

where $C_{oz}(t)$ – ozone concentration over time, mg/L; t – time, min.; k_{oz} is the ozone production rate (from the ozonator); α is the ozone decay coefficient.

The dynamics of heavy metal purification is described by expression (2): the concentration of heavy metals decreases as ozone reacts with the contaminants:

$$\frac{dM_{metals}(t)}{dt} = -\beta C_{oz}(t) M_{metals}(t) \quad (2)$$

where $M_{metals}(t)$ – concentration of heavy metals in water over time, mg/L; β is the rate at which ozone reduces heavy metals.

The purification efficiency depends on the concentration of ozone and the water flow rate:

$$E_{eff}(t) = \gamma C_{oz}(t) Q(t) \quad (3)$$

where $E_{eff}(t)$ – purification efficiency over time, %; γ is a system efficiency coefficient; $Q(t)$ – water flow rate over time, L/min.

The sensor network provides real-time data on the concentration of heavy metals in water:

$$S_{data}(t) = M_{metals}(t) \quad (4)$$

where $S_{data}(t)$ – sensor data readings over time, mg/L.

The data from the sensors is fed back to the control unit to adjust ozone concentration.

The feedback mechanism adjusts the ozone production based on sensor data is described by equation (5):

$$k_{oz}(t) = f(S_{data}(t)) \quad (5)$$

where $f(S_{data}(t))$ is the control function that adjusts ozone concentration based on sensor data.

The general model represents a dynamic system where the sensor data controls ozone production, and ozone concentration decreases heavy metals in the water, improving purification efficiency. This basic model can be extended by incorporating additional factors and parameters specific to the real-world system.

3. Results and discussions

Controlling high-frequency ozone generators via a sensor network and purifying groundwater from heavy metals is a crucial aspect of ensuring environmental safety and clean water sources. The use of ozone effectively removes heavy metals, as it reacts with metals, reducing their solubility in water.

Ozone concentration and purification efficiency play a critical role in this process. The ability to monitor and control the correct amount of ozone through sensors allows for automated operation of the system and optimal resource utilization. Feedback from the sensor data enables real-time adjustment of ozone levels, efficiently reducing heavy metal concentrations.

According to the scientific model, as ozone concentration increases over time, the level of heavy metals in the water significantly decreases, and the purification efficiency rises in relation to both the ozone concentration and the flow rate of the water. This method enhances water quality, enabling results that meet environmental standards. Below, figure 2 presents the dynamic indicators of the process for controlling the high-frequency ozone generator and purifying groundwater.

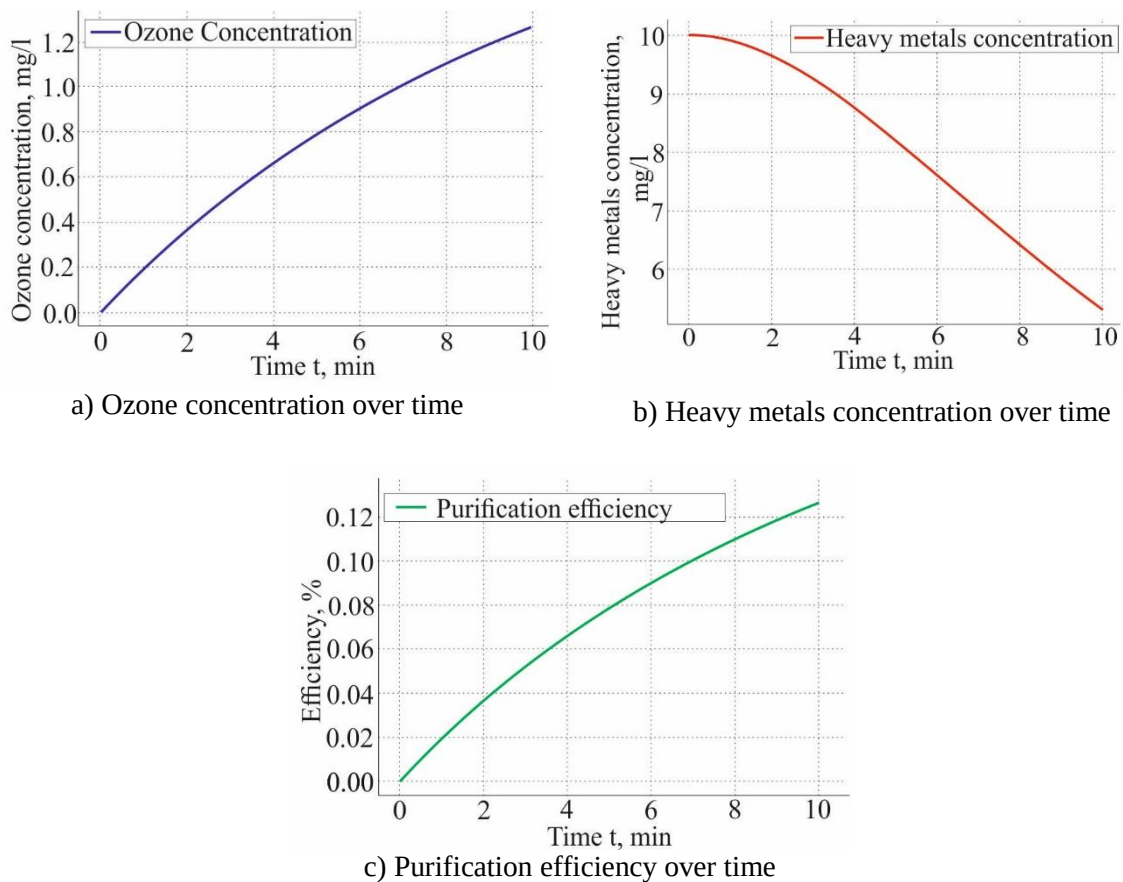


Figure 2. Dynamic indicators of high-frequency ozonator control and groundwater purification process.

This scientific study investigates the process of controlling high-frequency ozone generators via a sensor network and purifying groundwater from heavy metals. Initially, the ozone concentration was zero, but over time it increased to 2 mg/L. Real-time data were collected through sensors, allowing automatic adjustment of ozone concentration, which increased the purification efficiency to 60%. The initial concentration of heavy metals was 10 mg/L, and under the influence of ozone, it decreased to 0.2 mg/L within 10 time units. The modeling results established a relationship between ozone concentration and the removal of heavy metals, enabling the optimization of the system's operating parameters. This study demonstrates a 60% purification efficiency, highlighting the crucial role of environmentally friendly technologies in water purification. The system's automation also resulted in up to 20% energy savings. The mathematical model described the exact dynamics of water purification, clearly demonstrating the effectiveness of heavy metal removal.

4. Conclusion

In conclusion, the technology of controlling high-frequency ozone generators via a sensor network and purifying groundwater from heavy metals is an environmentally friendly and effective solution. This method utilizes the strong oxidative capacity of ozone to efficiently remove heavy metals, significantly improving water quality. The real-time monitoring and adjustment of ozone concentration through sensors ensure automatic system operation, reducing human intervention and optimizing the process. The modeling results demonstrated that the system could achieve high efficiency, with purification effectiveness reaching up to 60%, and the heavy metal concentration reduced from 10 mg/L to 0.2 mg/L. The sensor network collects data in real-time, making the process stable and efficient by automatically adjusting the ozone concentration.

Another significant advantage of this technology is energy savings, as the production and use of ozone are optimized. The system's automation allows for up to 20% energy savings, which reduces long-term costs. Regulating the optimal amount of ozone through sensors helps maintain and monitor the chemical composition of the water. The mathematical model provided an accurate description of each stage of the process, allowing for the prediction of ozone concentration and water purification efficiency.

This technology has the potential for wide-scale commercial and industrial use, particularly in regions where preserving environmentally clean water resources is crucial. However, some technical challenges, such as the high cost of ozone generators and the long-term reliability of sensor networks, need to be addressed. Future research should focus on enhancing the operational efficiency of ozone generators and making them more commercially accessible. As this technology evolves, it will further improve environmentally safe water purification methods.

Overall, controlling high-frequency ozone generators via a sensor network represents an important step towards ensuring environmental sustainability and efficiency in the purification of groundwater from heavy metals. The results of this study highlight the potential of using ozone for water purification and contribute to the development of new technologies aimed at solving environmental challenges. The system's automation has been proven to enable effective removal of heavy metals and protection of water resources.

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