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Wastewater treatment technologies using electrical discharge after processing of mineral raw materials

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Abstract

Purpose. The research aims to study wastewater treatment technology using electrical discharge at the Aktogay field in Kazakhstan to assess its effectiveness in reducing heavy metal concentrations and improving water quality.

Methods. Laboratory tests were conducted on a specially designed experimental setup operating in the voltage range from 15 to 100 kV and frequencies from 50 Hz to 10 kHz. Physical-chemical parameters of water (pH, electrical conductivity, temperature), concentrations of heavy metals (copper, zinc, cadmium) before and after treatment were measured. Mathematical models were used to describe the precipitation processes and to assess the purification efficiency.

Findings. Electrical discharge technology has been found to achieve a purification rate of up to 97.5% for copper, 97.3% for zinc and 96% for cadmium. At optimal parameters (15 kV, 10 kHz), heavy metal concentrations are reduced to levels that comply with World Health Organization standards. Improvement of physical characteristics of water (colour, odour, electrical conductivity) confirms the high efficiency of the method.

Originality. For the first time, an innovative wastewater treatment methodology based on electrical discharge technology, implemented using a specially designed device, has been developed and tested. Mathematical models of heavy metal removal processes that describe the kinetics and dynamics of pollutant precipitation have been proposed and experimentally confirmed.

Practical implications. The obtained results demonstrate a high potential for the industrial application of electrical discharge technology for treatment of wastewater generated during the processing of mineral raw materials at the Aktogay mine. Implementation of this technology will improve the environmental safety of production, while reducing operating costs and ensuring the possibility of water reuse.

Keywords: *wastewater, electrical discharge, heavy metals, water treatment, purification efficiency*

1. Introduction

1.1. Setting of a research problem

Kazakhstan is located in Central Asia and is the largest country in this region by area, ranking ninth in the world by size of the territory. The country has extensive borders with states such as Russia to the north, China to the east, Kyrgyzstan, Uzbekistan and Turkmenistan to the south and southwest. The political map of Kazakhstan is shown in Figure 1 [1]-[4]. The country's geographical location provides it with strategic importance at the crossroads of important transport and economic corridors between Europe and Asia.

Kazakhstan is characterized by abundant mineral-raw resources, including significant reserves of copper, zinc, lead and other metals. The Aktogay field, one of the largest copper deposits in Kazakhstan and Central Asia, is located in the east of the country, producing about 100 million tons of ore annually [5]. The Aktogay field is characterized by an open-pit mining method and a developed ore-processing infrastructure, making it a key element of the region's economic development.

Figure 1. Political map of Kazakhstan

The development of the mining industry in the area has a significant impact on Kazakhstan's economy, contributing to the country's exports and industrial production. However, intensive field development is accompanied by a number of environmental challenges, such as wastewater pollution caused by the content of heavy metals and chemical compounds, which requires the use of modern purification and pollution

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control technologies. Current research emphasizes the importance of environmentally friendly technologies in Kazakhstan in various sectors ranging from chemical industry [6] and agriculture [7], to the transition to renewable energy sources [8] and industrial waste recycling [9], which makes the development of innovative wastewater treatment methods, including the use of electrical discharge, particularly relevant.

The map of metal mining and export destinations at the Aktogay plant is shown in Figure 2 below [10], [11]. This large-scale production contributes significantly to the economic development of the country, but also causes environmental problems. Production processes annually generate about 30 million cubic metres of wastewater containing high concentrations of heavy metals and chemical compounds. Pollutants have a negative impact on the environment and disturb the ecological balance in the region.

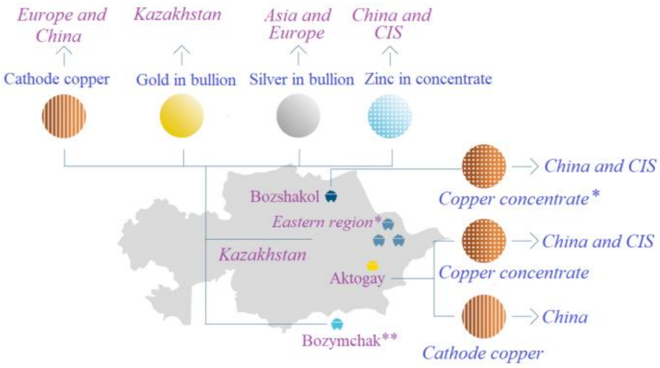

Figure 2. Map of metal mining and export destinations at the Aktogay plant in Kazakhstan [11]

**Contains by-products in the form of gold and silver in concentrate*
***Cathode copper, as well as gold and silver ingots, are produced from copper concentrate at the Balkhash Copper Smelter on a give-and-take basis*

Currently, various methods of wastewater treatment are used worldwide [12]-[16]. However, most require complex infrastructure or are costly [17]. For example, physical-chemical purification methods can remove only 70-80 per cent of heavy metals, while the removal efficiency of some organic compounds can be less than 50%. These restrictions necessitate the search for efficient and environmentally sound technologies for industrial wastewater treatment [18].

The method of wastewater treatment using electrical discharges has recently been of great interest, as studies have shown that this approach can remove more than 90% of heavy metals. In addition, the cost of electrical discharge technology is 20-30% lower compared to other methods, making it attractive for industrial applications [19], [20].

Aktogay mine, where copper is mined in an open-pit method, is the ideal location to implement this technology. Mine sulphide ores contain a high concentration of copper, which is beneficiated using flotation. The proximity of recycling plants further enhances the purification process efficiency (KAZ Minerals, 2023) [11]. Preliminary studies have shown that wastewater contains copper at a concentration of 20 mg/l, zinc at 15 mg/l, and cadmium at 0.5 mg/l, which exceeds the permissible concentration levels set by the World Health Organisation (WHO). Reducing these concentrations through electrical discharge treatment is important for both environmental sustainability and economic viability.

To improve the efficiency of electrical discharge technology, it is necessary to optimize the technical parameters of the purification system. Studies have shown that the use of 15 kV high-voltage electrical discharge and 10 kHz current frequency significantly improves the purification efficiency. This method not only effectively removes heavy metals, but also successfully decomposes organic compounds. Preliminary experiments show that purification efficiency can reach up to 90% [21], [22].

The main purpose of this research is to study the technology of wastewater treatment based on electrical discharges at the Aktogay field and assess its effectiveness in reducing the concentration of pollutants.

To achieve this purpose, the following objectives have been set:

1. Determine physical-chemical properties of wastewater samples from the Aktogay field.
2. Investigate the influence of electrical discharges on the concentration of pollutants.
3. Assess purification efficiency under laboratory conditions.
4. Develop recommendations for the implementation of technology in industrial conditions based on the research results.

The application of electrical discharge technology to treat wastewater from mineral processing at the Aktogay field represents a sustainable solution to improve the environmental situation and reduce pollution. This method has the potential to form the basis for future water reuse strategies through the efficient and safe disposal of waste from the metallurgical industry.

1.2. Analysis of modern wastewater purification methods

Various wastewater purification systems are currently in use around the world, each of which provides different technical and environmental results [23]-[25]. Basic water treatment methods include physical, chemical and biological approaches, each with its own levels of effectiveness and restrictions [26], [27]. Mathematical models for these three methods can be described by the following equations, which are used in planning and assessing the pollutant removal efficiency of water treatment process. Traditional methods based on infiltration through filter layers and infiltration basins have also been widely studied in [28]-[31], however, they are often accompanied by problems of colmatation and require large areas for effective functioning.

The filtration model (physical method) describes the relationship between water flow rate Q and filter resistance R in the filtration process as follows:

$$Q = \frac{\Delta P}{R}, \qquad (1)$$

where:

ΔP – pressure differential across the filter.

This model is used to determine the filtration efficiency depending on the type and properties of the filter material.

The coagulation and flocculation model (chemical method) is a model describing the relationship between coagulant dosage D and the degree of water purification:

$$C_t = C_0 e^{-kDt}, \qquad (2)$$

where:

C_t – concentration over time t;
C_0 – initial concentration;
k – coefficient characterizing reaction efficiency.

This model is used to optimize the dosage of coagulants and to determine the required amount of reagent to improve water quality.

Biological purification model (biological method) describes an aerobic purification process, in which biomass growth and pollutant level reduction are expressed as follows:

$$\frac{dX}{dt} = \mu X - k_d X \frac{dS}{dt} = -\frac{1}{Y}\mu X + k_d X, \tag{3}$$

where:

X – biomass concentration;
S – pollutant level;
μ – growth rate;
k_d – death rate;
Y – growth efficiency.

The presented model is used for design planning of bioreactors and assessing their performance. It also allows modeling of bacterial growth and pollutant removal efficiency.

Table 1 presents a comparative analysis of different wastewater treatment methods: physical, chemical and biological in terms of their effectiveness and restrictions. Physical methods are highly effective in removing mechanical impurities, while chemical and biological methods play a key role in removing organic pollutants and ensuring environmental sustainability. However, despite their effectiveness, each of the methods has certain restrictions. For example, chemical methods require the use of reagents that may pose a threat to the environment, while physical methods are insufficient to completely remove organic compounds. In this regard, it is appropriate to examine the use of electrical discharge-based wastewater purification technology, developed for the treatment of wastewater generated during the processing of mineral raw materials at the Aktogay field. This method is highly effective in removing both organic pollutants and heavy metals, while reducing environmental pollution.

Table 1. Effectiveness and restrictions of different wastewater purification methods [32], [33]

Purification methods	Principle of action	Efficiency	Restrictions
Physical methods	Mechanical separation	Effectively remove particles	Insufficient for complete removal of organic matter
Filtration	Separation of solids using screens or membranes	Capable of capturing particles smaller than 0.1 µm	Membrane wear; frequent cleaning required
Settling-out	Settling of solid particles by gravity	Effectively removes coarse and heavy particles	Ineffective for light and fine particles
Centrifugation	Particle separation using centrifugal force	Separates particles quickly and efficiently	High energy consumption; expensive equipment
Chemical methods	Purification using chemical reactions	Highly effective against organic substances and microorganisms	Chemical residues; potential environmental damage
Coagulation and flocculation	Combining small particles into large particles using reagents	Effectively removes high pollutant concentrations	Residual floccules must be removed after treatment
Ozonation	Use of strong ozone oxidative properties	Extremely effective against viruses and bacteria	Difficulty in precise dosing; high cost
Biological methods	Purification using microorganisms	Environmentally friendly; effectively remove stubborn pollutants	Time-consuming; require careful quality control
Aerobic purification	Microorganisms decompose pollutants with oxygen	Capable of decomposing various organic substances	Efficiency depends on sufficient oxygen level
Anaerobic purification	Biological decomposition without oxygen access	Effective for removal of stubborn organic pollutants	Less effective than aerobic methods
Artificial systems	Examples: biofilters, active sludge systems	Long-term and effective purification	Require complex and expensive equipment

1.3. Efficiency and environmental safety of electrical discharges during water purification

Plasma chemical processes are the basis of electrical discharge technology. Under the influence of a high-frequency electric field, pollutants dissociate, forming active radicals that destroy them [34], [35]. This process effectively degrades both organic and inorganic pollutants contained in water [36]. The advantages and unique characteristics of water purification using electrical discharge are summarized in Table 2 below.

As shown in Table 2, the water purification method using electrical discharge is environmentally friendly, as no additional chemical reagents are required. Moreover, this method is highly energy efficient, consuming relatively little energy while providing over 95% efficiency in the removal of heavy metals and stubborn organic pollutants. Energy efficiency of water purification using electrical discharge is shown in Figure 3 below [37].

Table 2. Environmental and efficiency aspects of electrical discharge in water purification [38], [39]

Aspect	Description
Purification process using electrical discharge	Plasma chemical processes occur; pollutants decompose under the action of an electric field, forming radicals
Environmental safety	No chemical reagents are used, making the method environmentally safe
Scope of application	Applicable for removal of a wide range of organic and inorganic substances
Efficiency	Effective in breaking down heavy metals and stubborn organic pollutants
Energy saving	Consumes comparatively less energy
Differences from other methods	Operates at room temperature without the need for high temperatures or pressure; achieves results faster than biological treatment methods

Figure 3 shows the reduction in energy consumption as the water purification efficiency increases with the use of electrical discharge. By increasing the purification efficiency from 85 to 95%, the energy consumption is reduced from 0.8 to 0.5 kW·h, demonstrating the high energy efficiency of this process.

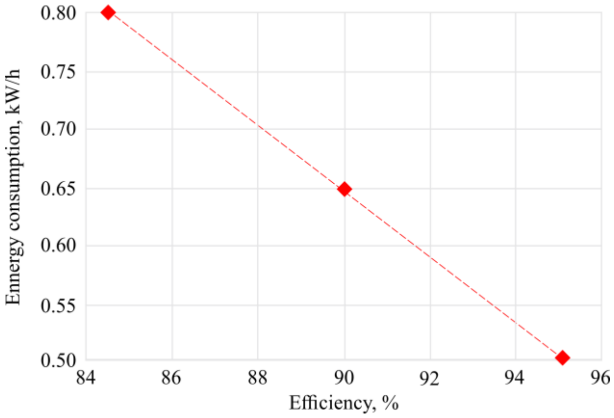

Figure 3. Energy efficiency of water treatment using electrical discharge at different levels

1.4. Review of water purification methods at the Aktogay mine

Industrial processes used at the Aktogay mine generate wastewater containing heavy metals (copper, zinc, cadmium) and other harmful substances [40]-[42]. Therefore, researchers continue to study the effectiveness of different water purification methods. Figures 4a and 3b below show a scheme of the mining and processing facilities at the Aktogay mine [11].

Figure 4a presents an aerial photograph of a water treatment plant at the Aktogay field, showing large blue circular water tanks and extensive network of pipelines that are key elements in the water purification process at the facility. Figure 4b illustrates the layout of mining and processing facilities at the Aktogay field, including the primary crushing facility, beneficiation plants and various waste storage sites.

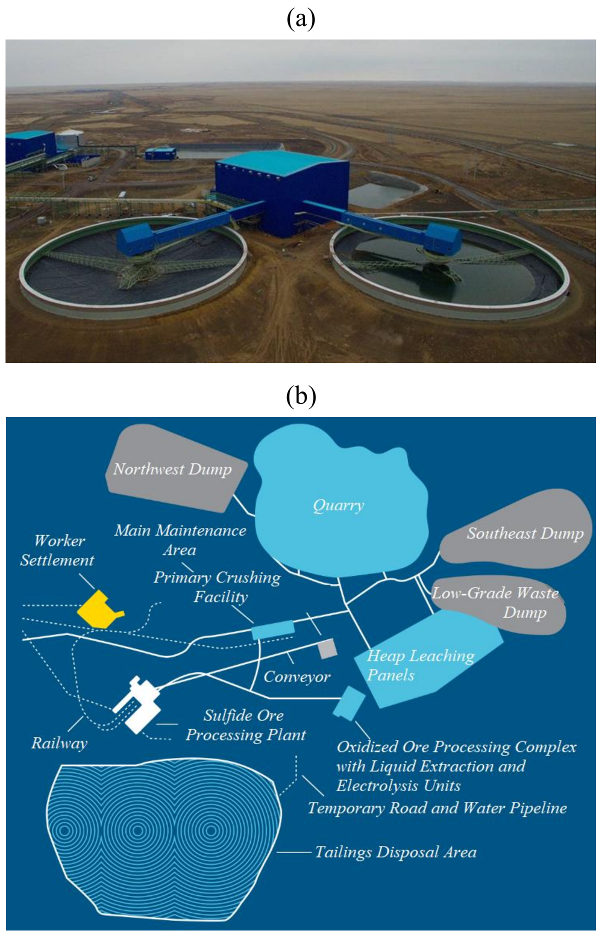

Figure 4. Water purification and processing infrastructure at the Aktogay mine: (a) aerial photograph of the water treatment plant at the Aktogay mine; (b) layout of mining and processing complex at the Aktogay field

Table 3 shows wastewater chemical composition, characteristics and its impact on the environment.

Table 3. Chemical composition of wastewater and its environmental impact

Components	Initial values, mg/l	Permissible levels, mg/l	Environmental impact
Chlorides (Cl)	150	250	Affect the salinity and pollution of groundwater
Sulphates (SO_4^{2-})	250	250	Damage aquatic ecosystems, cause disturbances
Iron (Fe^{3+}, Fe^{2+})	0.3	0.3	Toxic to aquatic life, may cause corrosion
Copper (Cu)	20	1.0	Toxic to aquatic life, indicates industrial pollution
Zinc (Zn)	15	5.0	Toxic to fish and other aquatic organisms
Fluorides (F)	0.5	1.5	Has a harmful effect on humans and animals
Calcium (Ca)	100	200	Increases water hardness, affects calcium cycling
Bromides	–	Not specified	Potentially toxic to organisms
Ammonium (NH_4^+)	0.5	0.5	Disrupts the nitrogen cycle in aquatic ecosystems
Nitrites (NO_2^-)	0.2	1.0	Indicates nitrogen fertilizer pollution, promotes algae growth
Nitrates (NO_3^-)	10	50	Promotes algae growth, worsens water quality
Heavy metals	0.01	0.01	Extremely toxic, indicating industrial and mining pollution
Total dissolved substances	500	1000	Increases salinity, affects aquatic ecosystems
Cadmium (Cd)	0.5	0.003	Extremely toxic, accumulates in aquatic organisms, affects human health

Based on the data presented in Table 3, the concentrations of elements such as copper (Cu), zinc (Zn) and cadmium (Cd) exceed the maximum permissible concentration (MPC), indicating pollution caused by industrial and mining activities.

These elements pose a serious threat to aquatic ecosystems and human health, which requires reducing their concentrations and implementing strict control measures.

2. Research methods

2.1. Research execution procedure

To assess the efficiency of the electrical discharge method for treating wastewater generated during ore processing at the Aktogay field, a diagram of the interaction between treatment methods and pollutants is used, as shown in Figure 5.

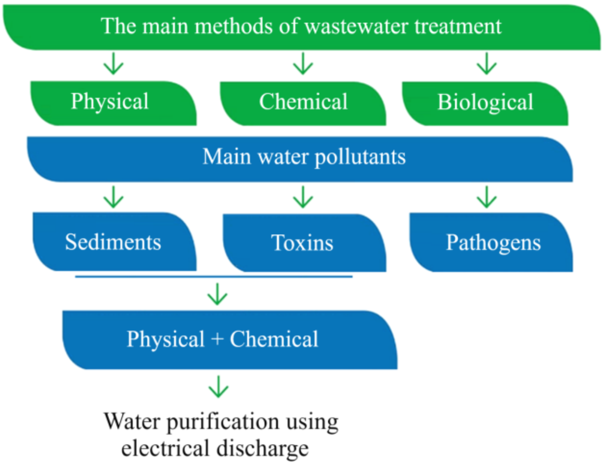

Figure 5. Diagram of interaction between wastewater treatment methods and pollutants

Figure 5 shows the planned methodology of scientific research, which includes the interaction of physical, chemical and biological methods of water treatment along with the purification technology using electrical discharge.

The research methodology consists of the following steps:

1. Determination of physical-chemical characteristics – sampling of wastewater from the Aktogay mine and analysis of its physical-chemical parameters, including pH, viscosity, chemical oxygen demand (COD), biochemical oxygen demand (BOD), as well as heavy metal concentrations.
2. Study of the impact of electrical discharge – observation of the dynamics of pollutant concentration during the purification process using electrical discharge. This step involves adjusting the parameters: voltage, current intensity and frequency to optimize purification.
3. Assessment of purification efficiency – analyzing the water treatment results in laboratory conditions and investigating changes in wastewater pollution levels.
4. Development of recommendations for industrial implementation – based on the results obtained, specific recommendations are formulated for the integration of purification technology using electrical discharge into industrial practice, taking into account its economic efficiency and environmental safety.

The following sections detail the experiments, physical-chemical analysis methods and water quality measurements used to assess the effectiveness of the electrical discharge technology in treating wastewater from the Aktogay mine.

2.2. Experimental setup

To achieve the purpose of the scientific research, the following objectives were set: to determine the physical-chemical characteristics of wastewater samples from Aktogay mine; to study the effect of electrical discharge on the concentration of pollutants; to assess the efficiency of the purification process under laboratory conditions; based on the research results, to prepare recommendations for the implementation of technology in industrial conditions.

To implement these objectives, a joint study was conducted with Satbayev University and Tashkent Institute of Irrigation and Agricultural Mechanization Engineers. As part of the scientific research, a device for water disinfection and purification using electrical discharges was developed, protected by a special patent [43], [44]. The schematic diagram of the device is shown in Figure 6.

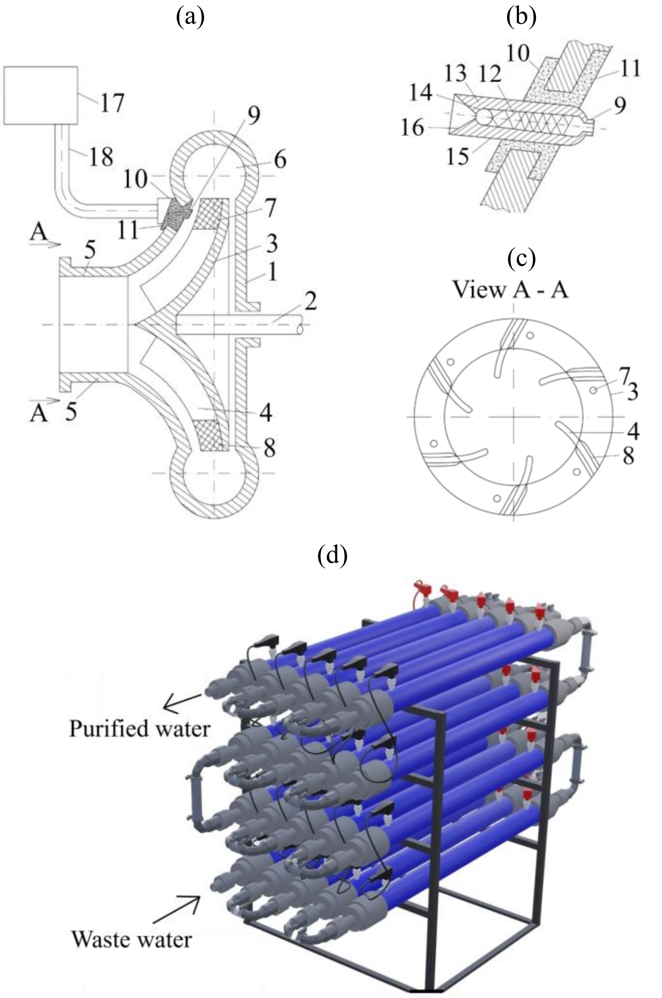

Figure 6. Device for water disinfection using electrical discharges: (a) side section of the device; (b) side section of the stationary electrode; (c) impeller blades with electrodes; (d) general view of the device

The device for water disinfection using electrical discharges includes a housing *1*, inside which a freely rotating impeller *3* with blades *4* is mounted on a shaft *2*. The housing *1* is equipped with an inlet collector *5* and an outlet collector *6*. Along the periphery of the impeller *3*, in the area of the blades *4*, on the side opposite to the direction of wheel rotation, electrodes of the same sign *7* ("–"), grounded to the housing *1*, are mounted. Between the electrodes *7* and the blades *4*, there are reflectors *8* made of material resistant to the destructive effects of electro-hydraulic shocks. These reflectors cover the blades *4* and are fixed to the radius of the stationary mounted electrodes *7*.

The stationary electrode *9* of opposite sign (usually "+") is insulated from the housing *1* with a sleeve *10* made of insulating material, placed in protective covers *11*, preventing the possibility of electrical breakdown on the housing of electrodes *7*. The stationary electrode *9* includes an outlet channel *12* with a minimum longitudinal section at the outlet and an element *13*, insulated at the front, for placing a return valve *14* with a spring *15*. The spring *15* lifts the valve *14* to the outlet opening (nozzle) of the element *13* at its inlet, where the diffuser *16* is mounted, connecting the outlet channel *12* with the atmosphere when the valve *14* is opened. Spring *15* is a double spring comprising two coils nested inside each other, twisted in opposite directions.

The device is equipped with a current pulse generator *17*, one pole of which is connected via a high-voltage shielded cable *18* to the stationary electrode *9* and the other to the housing *1*. Generator *17* can generate pulses with voltage from 5 to 100 kV and frequency from 0.1 to 100 Hz with efficiency from 0.85 to 0.95.

The principle of the device operation is as follows: through the inlet collector *5*, the housing cavity is filled with process fluid, and high voltage is supplied from the generator *17* via cable *18* to electrodes *7* and *9*. When the impeller *3* rotates, for example by movement of pre-compressed fluid in the cavity or by other means, the distance between the stationary electrodes and the nearest movable electrodes *7* decreases, reaching a minimum value. At this moment, the optimum voltage of the current source – generator *17* – is selected. If the distance between electrodes *7* and *9* corresponds to the calculated values, a spark discharge occurs in the interelectrode space. The blade *4* through the deflector *8* receives a mechanical impulse in the direction of impeller *3* rotation by displacing fluid from the inter-blade channel into the outlet collector *6*. This is caused by the release of electrical energy in the discharge channel, followed by the subsequent combustion of dissociated organic pollutants of the air entering the discharge channel from the atmosphere through the diffuser *16* (Fig. 6b), valve *14* and channel *12*, when the pressure in it drops below atmospheric pressure and the maximum tension value of the spring *15* is reached. Providing the ratio of these pressures about two and the ratio of sectional areas about four at the outlet of the channel *12* makes it possible to implement the critical mode of air flow into the discharge channel, at which its maximum flow rate is achieved, that is, the highest efficiency of the device operation is ensured.

The impeller rotation velocity of the device for disinfecting water with organic impurities is regulated by changing the power of the generator current pulses while achieving an increased efficiency of action on the purified liquid. The device can also be used, for example, in installations for presowing preparation of seeds of various agricultural crops, where seeds are subjected to water treatment with simultaneous exposure to a complex of factors that enhance their physiological activity: hydraulic shock, electromagnetic field, light and thermal radiation, ultrasound, etc. All this further contributes to increased crop yields and faster plant maturation. A promising direction is the creation of a submersible variant of the device based on the filter system, which opens up the possibility of creating new means for purifying water bodies due to mechanical, physical and chemical impact on the medium to be purified.

Analyzing the effect of electrical discharge on pollutant concentrations in industrial conditions is key to improving the efficiency of environmental cleaning technologies. This method allows for flexible adjustment of purification parameters depending on the concentration of different pollutants, including copper (Cu), zinc (Zn) and cadmium (Cd). The experiments were performed using a laboratory setup specifically designed for wastewater purification using electrical discharge, which operated in a voltage range from 15 to 100 kV and frequencies from 50 Hz to 10 kHz. Figure 7 presents the general view of the laboratory model.

(a)

(b)

Figure 7. Laboratory model based on electrical discharge: (a) general view of the model; (b) a generator operating at a voltage of 5-15 kV and a frequency of 10 kHz

The research analyzed changes in metal (Cu, Zn, Cd) concentrations in water at different current intensity and electrical discharge frequency. Dependences between electrical exposure parameters and the efficiency of pollutant removal were studied. Particular attention was paid to identifying the optimal operating modes of the setup, at which the highest purification efficiency is achieved at minimum energy consumption.

2.3. Assessment of the purification process efficiency under laboratory conditions

Heavy metal concentrations were measured before and after treatment to assess the efficiency of the purification process performed under laboratory conditions. The initial copper (Cu) concentration was 20 mg/l and after purification it decreased to 0.5 mg/l, corresponding to an efficiency of 97.5%. The initial zinc (Zn) concentration was 15 mg/l and after purification it decreased to 0.4 mg/l, giving an efficiency of 97.3%. The cadmium (Cd) concentration before purification was 0.5 mg/l and decreased to 0.02 mg/l, corresponding to an efficiency of 96%. Thus, the purification process using electrical discharge has demonstrated high efficiency under laboratory conditions, significantly reducing heavy metal concentrations.

Similarly, a mathematical model for heavy metal removal using electrical discharge based on laboratory data was studied during the scientific research. In particular, reaction kinetics aimed at reducing the concentrations of copper (Cu), zinc (Zn) and cadmium (Cd) was used. These reactions can be modeled using first-order kinetics, where the concentration decreases exponentially with time. For example, for copper ions, the reaction equation is as follows:

$$C(t) = C_0 e^{-kt}, \tag{4}$$

where:

$C(t)$ – copper concentration at the moment of time (t), mg/l;

C_0 – initial concentration, mg/l;

k – reaction velocity constant, 1/min;

t – time, min.

According to this model, knowing the value of the velocity constant k and the initial concentration C_0, the copper concentration at any moment of time t can be calculated. It is also possible to use the inverse regression method to determine the value of k from experimental data.

Efficiency assessment – purification efficiency E – can be calculated using the following Formula:

$$E = \left(1 - \frac{c(t)}{c_0}\right) \cdot 100\%, \tag{5}$$

where:

E – purification efficiency, %;

$C(t)$ – concentration at the moment of time (t);

C_0 – initial concentration.

Equations (7) and (8) can be used to analyze laboratory data and to predict purification processes, as well as help to determine optimal process parameters in the future.

3. Results

3.1. Physical-chemical characteristics of wastewater samples from the Aktogay mine

As part of the research, physical-chemical analyses on wastewater samples taken from the Aktogay mine were conducted. Results of the analysis are shown in Table 4. The primary wastewater composition contained copper (Cu) – 20 mg/l, zinc (Zn) – 15 mg/l and cadmium (Cd) – 0.5 mg/l.

Table 4 demonstrates the dynamics of physical-chemical changes during water purification process using electrical discharge for 50 min. As can be seen, there is a steady decrease in the concentrations of heavy metals such as copper, zinc and cadmium, as well as changes in basic water properties, including temperature, conductivity, pH, colour and odour. Temperature and electrical conductivity: the water temperature gradually increases from 20 to 25°C as the experiment progresses, reflecting the energy supply from the electrical discharge.

Table 4. Physical-chemical changes over time during water purification process using electrical discharge

Time, min	Temperature, °C	Electrical conductivity, µSm/cm	pH	Colour	Odour	Copper, mg/l	Zinc, mg/l	Cadmium, mg/l
0	20	1500	8.2	Light-yellow	Pungent, chemical odour	20	15	0.5
10	21	1480	8.1	Lightened yellow	More faint	14	9	0.25
20	22	1450	8.0	Pale yellow	Less pungent odour	8	5	0.10
30	23	1400	7.9	Almost transparent	Faint	3	2	0.08
40	24	1350	7.8	More transparent	None	1	No	No
50	25	1300	7.7	Transparent	None	0.5	No	No

Electrical conductivity decreases from 1500 to 1300 µS/cm, indicating a decrease in ion concentration, possibly due to deposition or decomposition of dissolved compounds.

pH and heavy metals: pH level decreases slightly from 8.2 to 7.7, which may indicate the formation of more acidic compounds or the removal of alkaline substances. Most importantly, the copper content decreases dramatically from 20 mg/l at the beginning to 0.5 mg/l at the end, demonstrating high removal efficiency. Zinc also shows a similar trend, from 15 mg/l to non-detectable level, as does cadmium, whose concentration decreases from 0.5 mg/l to non-detectable level by the 40th minute.

The change in colour from "light yellow" to "transparent" and the disappearance of a pungent chemical odour indicate the effective removal of a significant amount of organic and inorganic pollutants. These sensory changes are consistent with the expected results of successful electrical discharge treatment, in which the substances giving color and smell are destroyed. Our observations confirm that the purification technology using electrical discharge is effective not only in reducing heavy metal concentrations, but also in improving overall water quality by changing its appearance and chemical composition.

The metal removal process is implemented through electrical discharge, during which metal ions in water enter into complex chemical interactions. The electrical discharge causes ions to change to more neutral or easily removable forms. The chemical reactions that occur during the removal of heavy metal ions are discussed below.

Chemical reactions for copper (Cu), zinc (Zn) and cadmium (Cd):

$$Cu^{2+} + 2e^- \rightarrow Cu(s). \tag{6}$$

Copper ions take the electrons and precipitate as metal copper.

$$Zn^{2+} + 2e^- \rightarrow Zn(s). \tag{7}$$

Zinc ions also take electrons and precipitate as metal zinc.

$$Cd^{2+} + 2e^- \rightarrow Cd(s). \tag{8}$$

Cadmium ions take electrons and precipitate as metal cadmium.

Precipitation reactions occur on the electrode surface, where metal ions are reduced by joining electrons and converted into stable metal forms. Such processes are dependent on environmental conditions, including pH, temperature, electrical current stability, and other factors. In wastewater treatment using electrical discharge, the key point is to provide sufficient quantities of electrons to effectively neutralize metal ions and to cause their subsequent precipitation. The efficiency of the metal removal process using electrical discharge is illustrated in Figure 8.

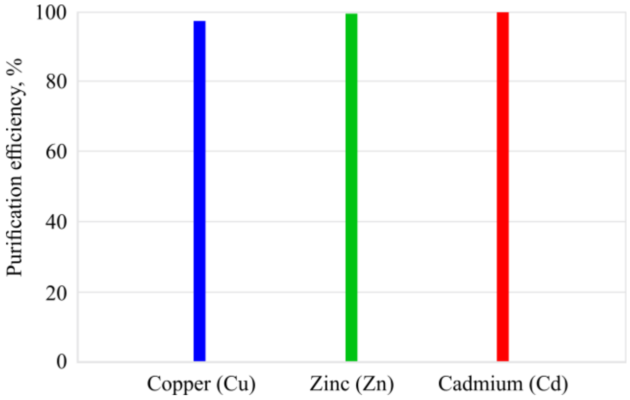

Figure 8. Efficiency of the metal removal process using electrical discharge

Figure 8 clearly demonstrates the effectiveness of metal removal process by means of electrical discharge. The bar chart shows that the purification efficiency for copper, zinc and cadmium are 80, 60 and 100% respectively, with cadmium being completely removed under the conditions used.

3.2. Effect of electrical discharge on pollutant concentrations

During the research of changes in the concentration of metals (copper, zinc, cadmium) in water at varying current intensity and frequency of electrical discharge, a regular dynamics of these parameters was observed. Table 5 demonstrates the efficiency of the purification technology using electrical discharge, which significantly reduces the heavy metal concentration in wastewater. As the current intensity and frequency of electrical discharge increase, the copper, zinc and cadmium content decrease significantly, which indicates a high purification method efficiency, reaching up to 99%.

Table 5. Efficiency of reducing heavy metal concentration using electrical discharge

Pollutant	Current intensity, A	Frequency, Hz	Concentration, mg/l		Reduction, %
			initial	final	
Copper (Cu)	5	20	20	1.5	92.5
	10	50	–	0.5	97.5
	15	80	–	0.3	98.5
Zinc (Zn)	5	20	15	1.5	90
	10	50	–	0.4	97.3
	15	80	–	0.1	99.3
Cadmium (Cd)	5	20	0.5	0.05	90
	10	50	–	0.02	96
	15	80	–	0.003	99

Figure 9 shows the efficiency of reducing the heavy metal concentrations (copper, zinc and cadmium) using an electric discharge depending on the current intensity. As the current increases from 5 to 15 A, the efficiency increases significantly: the copper concentration decreases from 92.5 to 98.5%, zinc – from 90 to 99.3%, and cadmium – from 90% to 99%, which demonstrates the improved efficiency of the method when the current increases.

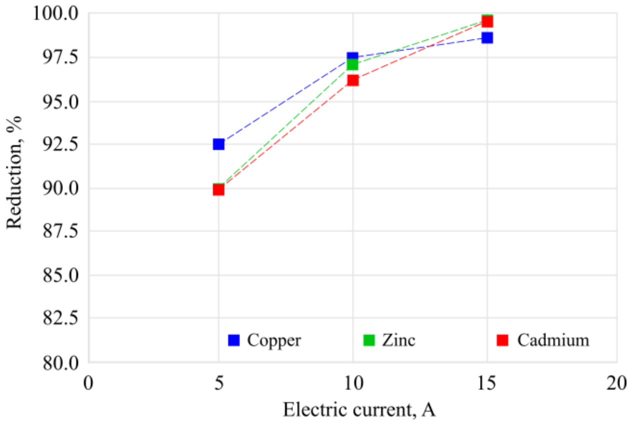

Figure 9. Efficiency of reducing heavy metal concentrations using electrical discharge

3.3. Recommendations for improving the efficiency of heavy metal purification in industrial conditions

The research results show a 96.0-97.5% decrease in heavy metal concentrations, which confirms the high potential of electrical discharge technology for industrial applications. Based on these data, the following recommendations have been developed for the implementation of this technology in industrial conditions. A system should be created that can reduce the initial concentration of copper ions of 20 mg/l to a level of 0.5 mg/l. Sensors and automation elements are required to improve process control and purification quality, which can reduce monthly industrial costs by up to 30%. In addition, improved annual maintenance and enhanced safety measures will contribute to improving workplace safety. The implementation of these measures will further improve purification efficiency in industrial conditions, making water treatment processes more cost-effective.

Figure 10 below shows the efficiency of reducing heavy metal concentrations using the electrical discharge method.

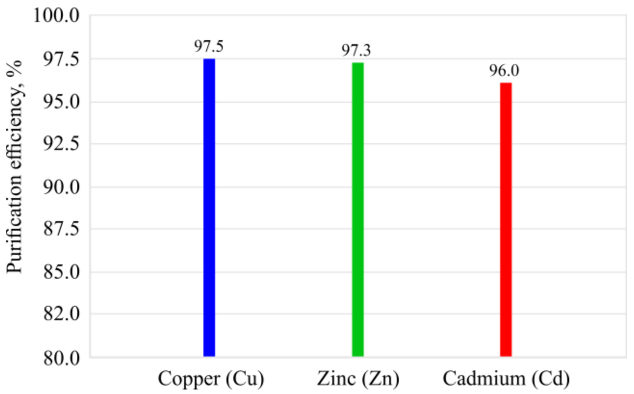

Figure 10. Efficiency of reducing heavy metal concentrations using electrical discharge

Figure 10 shows the percentage efficiency of heavy metal purification using electrical discharge. According to the results obtained, the purification efficiency of copper (Cu) is – 97.5%, zinc (Zn) – 97.3%, and cadmium (Cd) – 96%, which confirms the high efficiency of the electrical discharge method. Since the purification level of all metals exceeds 96%, this method seems to be very promising for industrial application when removing heavy metals from wastewater. The diagram also shows that the purification efficiency of copper and zinc is almost identical, while the purification efficiency of cadmium is slightly lower, but still reaches 96%. These data demonstrate that electrical discharge technology is an effective solution for industrial applications and has a high potential for real-world implementation.

4. Discussion

The research results confirm the high efficiency of wastewater treatment technology using electrical discharge. Laboratory tests have shown that this technology can achieve purification rates of up to 97.5% for copper (Cu), 97.3% for zinc (Zn) and 96% for cadmium (Cd), significantly exceeding the efficiency of conventional purification methods, which typically reach only 70-80%. The high efficiency is due to the ability of the electrical discharge to generate active particles (such as radical ions), which contribute to the reduction and precipitation of heavy metal ions without the use of additional chemical reagents, thus reducing the risk of secondary pollution and simplifying the purification process.

Particular attention should be paid to the dependence of the purification efficiency on electrical exposure parameters. It has been found that the highest degree of pollutant removal is achieved at a voltage of 15 kV and a frequency of 10 kHz. The set parameters provide an optimal combination of field strength and discharge frequency required to activate coagulation and metal ion reduction processes. The results obtained indicate that under these conditions, copper concentrations in wastewater decrease from the initial 20 to 0.5 mg/l, zinc to 0.4 mg/l, and cadmium to 0.02 mg/l, which is consistent with prescribed water quality standards (for example, WHO recommendations). The results obtained open up opportunities for water reuse in technological processes or for safe discharge into environment.

The practical importance of the research results is in the possibility of industrial implementation of electrical discharge technology, for example, at the Aktogay mine. For the successful implementation of this technology in industry, it is important to consider aspects such as process automation and installation of sensor-based monitoring systems to monitor purification efficiency in real time to ensure stable plant operation and rapid response to changes in wastewater composition. Further optimization of energy consumption can reduce operating costs by up to 30%, making the technology more cost-effective. Regular maintenance and staff training are also recommended to ensure the safe operation of high voltage equipment.

In addition, promising directions for further research include expanding the use of electrical discharge technology for the purification of wastewater containing both heavy metals and organic compounds, which will require the development of new, more corrosion-resistant and energy-efficient electrode materials, thus increasing the service life of the equipment. Pilot testing in industrial conditions is necessary to verify the reliability and performance of the technology at large-scale facilities. Also important is the integration of intelligent control systems, which will improve energy efficiency by 10-15% and reduce overall costs. Analysis of economic feasibility and comparative assessment with traditional purification methods will determine the long-term benefits of introducing electrical discharge into industrial wastewater purification system.

Thus, the research not only indicates the prospects of electrical discharge technology for wastewater purification from heavy metals, but also lays the foundation for further development and scaling of the method in industrial conditions.

5. Conclusions

The conducted research has confirmed the high efficiency of wastewater purification technology using electrical discharge. The application of this technology has achieved a purification rate of up to 97.5% for copper (Cu), 97.3% for zinc (Zn) and 96% for cadmium (Cd), significantly exceeding the efficiency of conventional purification methods. An important advantage of the method is the ability to remove heavy metals without the use of additional chemical reagents, which increases the environmental safety of the process.

Optimal parameters for achieving a high degree of purification are set at 15 kV voltage and 10 kHz of the electrical discharge frequency. Under these conditions, copper, zinc and cadmium concentrations in wastewater are reduced to safe levels, allowing the water to be reused or returned to the environment without damage to the ecosystem.

The practical importance of the research results is in the possibility of industrial implementation of this technology at the Aktogay mine to improve environmental safety and economic efficiency of water treatment. Electrical discharge technology can be considered as a promising solution for wastewater purification in the mining industry.

Author contributions

Conceptualization: SM; Data curation: AK; Formal analysis: SM; Funding acquisition: SA; Investigation: AK, DE; Methodology: SA; Project administration: AA; Resources: AI; Software: ZA; Supervision: AI; Validation: ZA; Visualization: DE; Writing – original draft: AA, AK, AI, DE; Writing – review & editing: AA, SA, SM, ZA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Технології очищення стічних вод із використанням електричного розряду після переробки мінеральної сировини

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Мета. Обґрунтування технології очищення стічних вод із використанням електричного розряду на родовищі Актогай в Казахстані для оцінки її ефективності у зниженні концентрації важких металів та поліпшенні якості води.

Методика. Лабораторні дослідження проводилися на спеціально розробленій експериментальній установці, що працює в діапазоні напруг від 15 до 100 кВ та частотах від 50 Гц до 10 кГц. Вимірювалися фізико-хімічні параметри води (рн, електропровідність, температура), концентрації важких металів (мідь, цинк, кадмій) до та після обробки. Для опису процесів осадження та оцінки ефективності очищення застосовувалися математичні моделі.

Результати. Встановлено, що технологія електричного розряду дозволяє досягти ступеня очищення до 97.5% для міді, 97.3% для цинку та 96% для кадмію. При оптимальних параметрах (15 кВ, 10 кГц) концентрації важких металів знижуються до рівнів, що відповідають нормам Всесвітньої організації охорони здоров'я. Поліпшення фізичних характеристик води (колір, запах, електропровідність) підтверджує високу ефективність методу.

Наукова новизна. Вперше розроблено та апробовано інноваційну методологію очищення стічних вод на основі технології електричного розряду, реалізовану із використанням спеціально сконструйованого пристрою. Запропоновано та експериментально підтверджено математичні моделі процесів видалення важких металів, які описують кінетику й динаміку осадження забруднюючих речовин.

Практична значимість. Отримані результати вказують на високий потенціал промислового застосування технології електричного розряду для очищення стічних вод, що утворюються при переробці мінеральної сировини на руднику Актогай. Впровадження цієї технології дозволить підвищити екологічну безпеку виробництва, знизити експлуатаційні витрати та забезпечити можливість повторного використання води.

Ключові слова: *стічні води, електричний розряд, важкі метали, очищення води, ефективність очищення*

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