



ХИМИЯЛЫҚ ИНЖЕНЕРИЯ
ХИМИЧЕСКАЯ ИНЖЕНЕРИЯ
CHEMICAL ENGINEERING

DOI 10.51885/1561-4212_2024_1_179
IRSTI 61.31

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OPTIMAL CONDITIONS FOR LIME TREATMENT OF MINE WASTEWATER FROM POLYMETALLIC ORE MINES

ПОЛИМЕТАЛЛ КЕНДЕРІН ӨНДІРУ КЕНІШТЕРІНІҢ ШАХТАЛЫҚ АҒЫНДЫ СУЛАРЫН ӘКПЕН ТАЗАЛАУДЫҢ ОҢТАЙЛЫ ЖАҒДАЙЛАРЫ

ОПТИМАЛЬНЫЕ УСЛОВИЯ ИЗВЕСТКОВОЙ ОЧИСТКИ ШАХТНЫХ СТОЧНЫХ ВОД РУДНИКОВ ПО ДОБЫЧЕ ПОЛИМЕТАЛЛИЧЕСКИХ РУД

Abstract. Mine waters of polymetallic mines are multicomponent systems containing ions of heavy non-ferrous metals, calcium, magnesium, iron, ammonium, as well as chlorides, sulfates, fluorides and other components in a wide range of concentrations. As a rule, water purification of this type is carried out by the lime method, which provides a fairly high degree of extraction of the most toxic pollutants (metals), with relatively small material costs. Taking into account the large volume, complexity and variation of the composition of mine waters, the tasks of optimizing reagent consumption, methods of its supply and effective control of the purification process still do not lose their relevance. The article presents the results of laboratory studies to determine the optimal conditions for processing model solutions that provide the maximum degree of purification for specific conditions of the Irtysh mine (East Kazakhstan). Experimental data obtained on model solutions are confirmed by the results of purification of real mine waste water. The results of experiments with mine water confirmed that the selected pH region of 9.5–10.5 can be accepted as optimal, which will allow achieving a high degree of purification of mine water.

Keywords: mine water, heavy metals, lime purification, hydrogen index (pH), precipitation of insoluble compounds.

Аңдатпа. Полиметалл кеніштерінің шахталық сулары құрамында ауыр түсті металл, кальций, магний, темір, аммоний иондары, сондай-ақ хлоридтер, сульфаттар, фторидтер және басқа да компоненттер бар көп компонентті жүйелерден тұрады. Әдетте, мұндай типтегі суды тазарту әктас әдісімен жүзеге асырылады, ол салыстырмалы түрде аз материалдық шығындармен ең ұлы ластаушы заттарды (металдарды) алудың жоғары дәрежесін қамтамасыз етеді. Шахталық сулардың үлкен көлемін, күрделілігі мен құрамының өзгеруін ескере отырып, реагенттің шығынын оңтайландыру міндеттері, оны беру әдістері және тазалау үднісін тиімді

бақылау әлі күнге дейін өзектілігін жоғалтпайды. Мақалада Ертіс кенішінің (Шығыс Қазақстан) нақты жағдайлары үшін тазалаудың ең жоғары дәрежесін қамтамасыз ететін модельдік ерітінділерді өңдеудің оңтайлы жағдайларын анықтау жөніндегі зертханалық зерттеулердің нәтижелері баяндалған. Модельдік ерітінділерден алынған эксперименттік деректер нақты шахталық ағынды суларды тазалау нәтижелерімен расталған. Шахталық сумен жүргізілген эксперименттердің нәтижелері таңдалған рН 9,5-10,5 аралығын оңтайлы деп қабылдауға болатындығын айғақтады, бұл шахталық ағынды суды тазартудың жоғары деңгейіне қол жеткізуге мүмкіндік береді.

Түйін сөздер: шахталық сулар, ауыр металдар, әкпен тазалау, сутегі көрсеткіші (рН), ерімейтін қосылыстардың тұнбасы.

Аннотация. Шахтные воды полиметаллических рудников представляют собой многокомпонентные системы, содержащие ионы тяжелых цветных металлов, кальция, магния, железа, аммония, а также хлориды, сульфаты, фториды и другие компоненты в широком интервале концентраций. Как правило очистка вод такого типа проводится известковым методом, который обеспечивает довольно высокую степень извлечения наиболее токсичных загрязняющих веществ (металлов), при сравнительно небольших материальных затратах. Учитывая большой объем, сложность и варьирование состава шахтных вод, задачи оптимизации расхода реагента, способов его подачи и эффективного контроля процесса очистки до сих пор не теряют своей актуальности. В статье изложены результаты лабораторных исследований по определению оптимальных условий обработки модельных растворов, обеспечивающих максимальную степень очистки для конкретных условий Иртышского рудника (Восточный Казахстан). Экспериментальные данные, полученные на модельных растворах, подтверждены результатами очистки реальной сточной шахтной воды. Результаты экспериментов с шахтной водой подтвердили, что выбранную область рН 9,5–10,5 можно принять в качестве оптимальной, что позволит добиться высокой степени очистки шахтной текущей воды.

Ключевые слова: шахтные воды, тяжелые металлы, известковая очистка, водородный показатель (рН), осаждение нерастворимых соединений.

Introduction. Water resources play an important role in social and economic development, and clean water is an environmental and social necessity identified in the UN Sustainable Development Goals [1, 2].

The most important environmental problem in the mining industry is the formation of a large volume of contaminated mine wastewater [3], which requires treatment, since the discharge of untreated wastewater into surface sources negatively affects the quality of water for fisheries and general purposes [4]. This problem is especially relevant in areas where mining enterprises are concentrated, which includes the East Kazakhstan region.

In world practice, mine water purification methods are usually limited to two methods - mechanical sedimentation [5] and chemical neutralization [6]. With known general patterns, each treatment plant has its own characteristics that affect the overall treatment efficiency.

In this regard, the problem of water purification is becoming increasingly urgent, which is reflected in a number of studies devoted to this topic.

To purify these wastewaters, reagent purification is usually used, in which heavy metal ions are converted into insoluble hydroxides using alkaline reagents [7].

The goal of this study was to establish the optimal operating mode of treatment facilities to achieve maximum efficiency in the treatment of mine wastewater using the example of wastewater treatment from the Irtysh mine located near the Altai village in the East Kazakhstan region.

In accordance with the set goal, the following tasks were solved:

- collection of statistical data on the composition of mine wastewater from the Irtysh mine;
- laboratory studies of the processes of precipitation of insoluble compounds of heavy metal ions in their joint presence from aqueous model solutions
- determination of the optimal dose of neutralizer (lime milk), ensuring maximum extraction of heavy metal ions in the form of insoluble compounds;

– finding partial analytical dependences of the degree of metal precipitation on the pH of the environment for mine waters of a specific deposit.

Treatment facilities for industrial mine water at the Irtysh mine have been in operation since 1975. During this time, significant changes have occurred both in the composition of mine waters coming for treatment and in the requirements for the quality of treatment.

It should be noted that the study of the chemical processes occurring during the purification of mine waters, which are multicomponent solutions of variable composition, will make it possible to select optimal conditions for lime cleaning, which makes the chosen research topic relevant.

The effectiveness of the reagent method for treating wastewater from heavy metals is determined by the completeness of the binding of metal ions into sparingly soluble hydroxides, which depends on a number of factors: the concentration of metal ions in wastewater, the pH value at which precipitation is carried out, the solubility of the resulting hydroxides, the possibility of the formation of complex compounds, the presence in purified water ions of iron, ammonium, etc. [8, 9].

According to [10], heavy metals are not completely precipitated from solutions by alkaline reagents, the pH ranges of precipitation of various ions differ significantly from each other, and acidity, which ensures sufficiently complete precipitation of one of the components, can lead to the dissolution of the hydroxide of another component, which is associated with amphoteric properties of heavy metals [11].

The range of optimal precipitation pH values differs significantly for different heavy metals. According to [12], when treating aqueous solutions with sodium hydroxide, heavy metal ions are quite completely precipitated by an alkaline reagent at pH 9-9.5. In addition, the combined presence of a large set of metal ions and anions in mine waters can significantly affect the precipitation of insoluble compounds due to the occurrence of complexation processes. Heavy metal ions are characterized by the formation of hydroxo-complexes and ammonia complexes, which reduces the efficiency of purification.

According to [13], copper and zinc ions form stable complexes with OH⁻ ions, the pK of complexes is 16, 15 and 14 for complexes [Cu(OH)₄]²⁻, [Zn(OH)₄]²⁻ and [Zn(OH)₃]⁻, respectively.

Cadmium, copper and zinc ions are characterized by the formation of stable ammonia complexes [Cd(NH₃)₄]²⁺ (maximum pK value = 7), [Zn(NH₃)₄]²⁺ (maximum pK value = 9) and [Cu(NH₃)₄]²⁺ (maximum value pK = 12) [13].

The novelty of the study lies in the fact that for the mine waters of a particular mine, the optimal conditions for the precipitation of insoluble compounds of heavy metals in their joint presence in solutions containing, in addition, sulfates, chlorides and nitrates were determined.

The obtained analytical dependencies can be used to assess the treatment efficiency of similar enterprises, which determines the practical significance of the study.

Materials and methods. The research was carried out using the methods of chemical experiment, physicochemical and chemical determination of the content of components in solutions, mathematical analysis of the obtained experimental data with the derivation of empirical equations describing precipitation processes.

Experimental studies to determine the optimal conditions for lime cleaning were carried out on model solutions with subsequent verification of the obtained optimal pH values on real mine water.

Materials:

a) metal salts:

– sulfates of copper, zinc, cadmium, manganese (II);

- iron (II) sulfate or chloride;
- calcium chloride;
- б) lime milk 3%;
- в) sodium sulfate to adjust the salt background.

The purification process was monitored by the residual content of metal ions in the treated model solution and real wastewater using approved methods.

Model solutions were prepared in accordance with the content of metal ions in real mine waters, selected based on statistical data from wastewater analysis during 2021. The composition of model solutions is presented in Table 1.

Table 1. Composition of model solutions used in the experiment

Ion	Cu ²⁺	Zn ²⁺	Cd ²⁺	Mn ²⁺	Ca ²⁺	Fe ²⁺	SO ₄ ²⁻
mg/dm ³	560	480	6.6	8.4	240	1	2,200

Lime milk was prepared from quicklime with an active CaO content of 65% as follows:

1. 30% lime milk was prepared, for which a sample of lime containing 300 g of active CaO was quenched in 700 mL of water, and the suspension was allowed to cool to room temperature;
2. The prepared suspension was diluted 10 times and used to precipitate metal ions.

The resulting suspension was used immediately after its preparation and activity analysis. To prevent the formation of calcium carbonate, storage without air access is possible.

The treatment of model solutions with lime milk was carried out as follows:

250 mL of the model solution was placed in a chemical heat-resistant beaker and mechanical or magnetic stirring was adjusted. Lime milk was added in small portions of 0.1÷1 mL, mixed thoroughly for 30–40 minutes, and the equilibrium pH value was measured. When the specified pH value was reached, the process was completed, the pulp was allowed to settle for 60 minutes, then the resulting mixture was filtered and the metal content in the filtrate was determined according to approved methods (Table 1), and the pH value was also measured.

After determining the optimal value of lime milk consumption, the results obtained were tested on real wastewater. The experiments were carried out taking into account the features of the wastewater treatment system adopted at the enterprise, which includes two stages:

- 1) chemical (neutralization with lime milk),
- 2) physical (mechanical deposition of sediment).

Both stages have their own conditions, the violation of which reduces the efficiency of work:

- a) chemical treatment requires a certain contact time after mixing mine water with the reagent and achieving the optimal pH (9.5–10.5);
- b) for mechanical sedimentation - this is the rate of supply, the point of delivery and the time of passage of water through radial settling tanks.

The results of the laboratory experiment were verified under real conditions as follows:

A sample of mine water was taken 1–2 hours before the end of pump operation. This ensured that the water would go through a full purification cycle in compliance with all conditions (contact time, settling time and passing through radial settling tanks). The next day, before the start of mine water supply, a water sample was taken from the drain part of the radial settling tank (upper part). At the time of sampling, pH was measured. Within an hour, the sample was transferred to the laboratory and the samples were analyzed for the components.

An examination of the operation of treatment facilities showed that, considering the free volume of contact tanks and the rate of supply of wastewater into them, the contact time of water supplied for treatment with lime milk is no more than 12 minutes, which is obviously not

enough to achieve the optimal pH value. Goal of the experiment: to confirm the hypothesis about the need to ensure contact time of mine water with reagents and maintain pH within optimal limits, allowing for maximum purification of wastewater from metal ions at the exit from treatment facilities. This goal is achieved by a time gap between the contact of mine water with the reagent (milk of lime) and the discharge of wastewater.

Results and discussions. The completeness of precipitation of sparingly soluble compounds of the general formula Me_aA_b is determined by their solubility product in accordance with the formula (1):

$$PS(Me_aA_b) = [Me]^a[A]^b \quad (1)$$

where, PS (Me_aA_b) is the product of the solubility of a sparingly soluble compound; [Me] – equilibrium concentration of the metal ion in solution; [A] – equilibrium concentration of the anion in solution.

Table 2 presents the calculated residual concentrations of metal ions in accordance with their solubility products, calculated from data on the composition of water entering treatment and discharged water according to the enterprise.

Table 2. Residual concentrations of metal ions in accordance with solubility products (concentrations of metal ions before and after purification at pH 8.52)

Ion	PS (solubility product)	Concentration according to the enterprise, mg/dm ³			Calculation
		Before treatment	After treatment	The standard established for the enterprise	
Cu ²⁺	$2.2 \cdot 10^{-20}$	11.32	0.017	0.00089	0.00013
Cd ²⁺	$5.9 \cdot 10^{-15}$	2,188	0.002	0.00069	0.605
Zn ²⁺	$1.2 \cdot 10^{-17}$	301.2	0.343	0.00337	0.0716
Mn ²⁺	$1.9 \cdot 10^{-13}$	12.89	0.029	0.00637	0.957

As can be seen from the calculated values obtained, the concentration of cadmium, zinc, and manganese ions at pH = 8.52 significantly exceeds the established discharge standards, which is due to the rather high value of the solubility products of their hydroxides. At pH = 10, it is theoretically possible to achieve discharge standards for zinc ions, but for cadmium and manganese ions, achieving the specified standards is impossible even at this pH value. Thus, the illogicality of the established discharge standards is obvious.

In accordance with the methodology described above, a series of laboratory experiments were carried out to determine the optimal consumption of lime slurry. The experimental results are presented in Table 3.

Table 3. Experimental conditions and consumption of lime suspension

Experiment number	Volume of model solution, mL	Initial pH	Final pH	Volume of lime milk, mL
1	250	6.01	6.60	1.2
2	250	6.01	7.00	1.6
3	250	6.01	7.5	3.5
4	250	6.01	8.03	4.0
5	250	6.01	8.54	4.1
6	250	6.01	9.10	4.3
7	250	6.01	9.50	4.5
8	250	6.01	10.00	4.9

Experiment number	Volume of model solution, mL	Initial pH	Final pH	Volume of lime milk, mL
9	250	6.01	10.56	5.6
10	250	6.01	11.00	6.0
11	250	6.01	11.53	7.7

The results of chemical analysis of water after treatment are presented in Table 4.

Table 4. Residual concentrations of the components of the model solution after treatment with lime milk

Experiment number/pH	Element, mg/dm ³							
	Cu	Zn	Cd	Mn	Ca	Fe _(total)	Fe ⁽²⁺⁾	S _(SO4)
1/6.6	3.1	340	6.6	8.4	330	0.99	<0.10	2,100
2/7.0	2.9	330	6.2	6.9	320	0.87	<0.10	2,100
3/7.5	2.4	60	5.2	6.0	420	0.75	<0.10	2,000
4/8.03	1.8	14	4.8	5.7	440	0.65	<0.10	1,900
5/8.54	1.4	8.8	3.6	5.3	460	0.6	<0.10	2,200
6/9,10	0.1	7.8	2.4	1.1	440	0.51	<0.10	1,900
7/9.50	0.1	1.2	2.3	0.9	440	0.46	<0.10	2,200
8/10.0	0.1	0.1	0.8	0.85	430	0.32	<0.10	2,400
9/10.56	0.1	0.1	0.4	0.8	440	0.12	<0.10	2,100
10/11.00	0.1	0.1	0.1	0.7	490	0.09	<0.10	1,900
11/11.53	0.1	0.1	0.1	0.5	540	0.01	<0.10	2,200
Composition of model mine water before treatment	560	480	6.6	8.4	240	2	1	2,200

The results of the analysis of the composition of filtrates indicate the possibility of deep purification of mine water in the pH range of 10–11, but not up to the standards established for the discharge of mine water from an enterprise.

Based on the results of the experiments, the dependences of the degree of precipitation of components on the pH of the filtrates were plotted (Figure 1), reflecting the nature of the process in the selected pH range from 6 to 11.5.

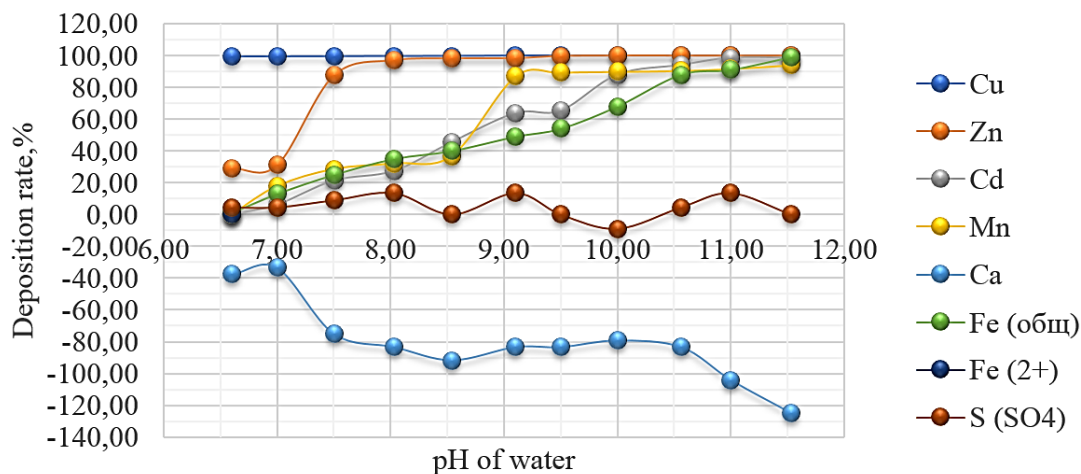


Figure 1. Dependence of the degree of precipitation of impurity components of the model solution on pH

Based on the study of the experimental results, partial analytical dependences of the degree of precipitation of impurity components on the pH of the medium were established, which satisfactorily describes the process of purification of model mine water within the selected range of pH changes (Table 5), which with a high correlation of 0.92÷0.99 describe the behavior of the components during precipitation in the selected range of pH changes.

Table 5. Partial analytical dependences of the degree of metal deposition on the pH of the environment

Element	Degree of deposition of impurity components, $Y_{(Me)}$	Correlation coefficient, k	Maximum achievable degree of deposition Y_{max} , %	pH range
Copper	$96.12 + 0.71X_{Cu} - 0.03X_{Cu}^2$	0.98	99.98	9.1 – 11.53
Zinc	$133.83X_{Zn} - 6.72X_{Zn}^2 - 557.95$	0.92	99.98	10 – 11.53
Cadmium	22.33; $X_{Cd} - 146.44$	0.99	98.48	11 – 11.53
Manganese	$83.1X_{Mn} - 426.74 - 3.8X_{Mn}^2$	0.96	94.05	11.53
Iron	$19.56X_{Fe} - 125.52X_{Fe}$	0.92	99.0	11.53

Based on the results of studies on the purification of the model solution - the residual concentrations of impurity components, the degree of their precipitation in the selected range of pH changes - from 6 to 11.53 - it was established that the most convincing indicators of purification with lime milk are achieved in the pH range of 9–11.

To check the results obtained under real conditions, two water samples were taken, the composition of which is given in Table 6.

Table 6. Results of chemical analysis of mine water samples

Sample	Element, mg/dm ³								
	Cu	Zn	Cd	Mn	Ca	Fe ⁽²⁺⁾	Fe _(total)	S _(SO4)	Cl
Mine water, sample No. 1	11	390	2.8	14	520	<1	5.8	2200	n/a
Mine water, sample No. 2	<1	230	<1	3.5	380	<1	400	n/a	110

Three experiments on lime precipitation were carried out with sample No. 1 within the optimal pH range of 9.55–10.48.

Conditions and results are shown in Tables 7 and 8.

Table 7. Experimental conditions and consumption of lime suspension for purifying water sample No. 1

Experiment number	Model volume solution, ml	Initial pH	Final pH	Volume of lime milk, mL
1	250	6.09	9.55	6.2
2	250	6.09	9.98	7.0
3	250	6.09	10.48	7.6

Table 8. Results of chemical analysis of purified mine water sample No. 1

Experiment	Element content, mg/L
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number	Cu	Zn	Cd	Mn	Ca	Fe	Sso ₄
1	1	1	1	1	800	1	-
2	1	1	1	1	820	1	-
3	1	< 1	1	1	870	1	-

One experiment was carried out with water sample No. 2 at pH 10 (which is within the optimal range) while other conditions were met. The results of the experiment are shown in Table 9.

Table 9. Results of an experiment on the purification of mine water sample No. 2 at pH 10

Sample	Element content, g/L							
	Cu	Zn	Cd	Mn	Ca	Fe _{total}	Sso ₄	Cl
Mine water No. 2	< 1	23	1	3.5	380	400	-	110
Solution after treatment	< 1	< 1	1	1	420	1	300	120

The results of experiments with mine water confirmed that the selected pH region of 9.5–10.5 can be accepted as optimal, which will allow achieving a high degree of purification of mine water. Although in this case, for objective reasons, the established standards for the discharge of treated mine water into the reservoir are not achieved.

Based on laboratory experiments on the purification of model solutions and real mine water, the completeness of wastewater purification from metal ions was assessed and a forecast was made for achieving standardized purification indicators depending on lime consumption (achieving a certain pH value). Figure 2 shows the dependence of the amount of lime consumption to achieve a certain pH value (the consumption is calculated for a volume of 1 m³ of active CaO in 100% lime).

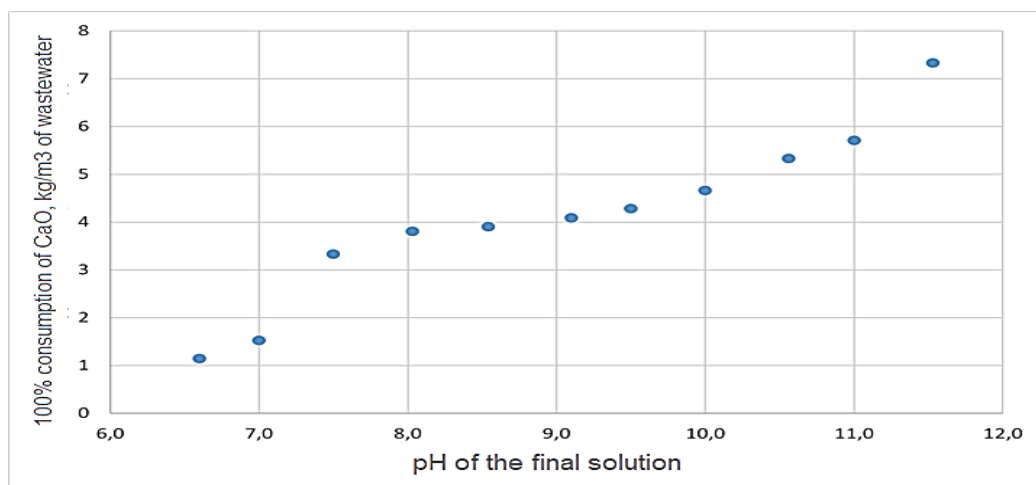


Figure 2. Dependence of CaO consumption in terms of 100% activity per 1 m³ of wastewater

As can be seen from the graph, a certain plateau is observed between 8 and 9 pH, when a change in the acidity of the solution occurs practically without the consumption of lime milk. This is most clearly visible in the differential graph (Figure 3). Three peaks of the main consumption of the reagent can be identified - 7.3; 10.3 and 11.3.

The first peak at pH around 7.0 is associated with the formation and precipitation of the bulk of insoluble compounds. Then a second peak is observed at pH around 10.0. Presumably, it is associated with the formation of soluble complex metal compounds from insoluble precipitates. Next is

the dilution of the solution with increasing pH, mainly due to the addition of an alkaline agent.

Figure 3 shows the dependence of CaO consumption on the concentration of the pollutant component.

As can be seen from Figure 3, to ensure an optimal pH for the precipitation of metals, constant addition of lime is required, which leads to an increase in calcium in the solution because of the decomposition of CaO.

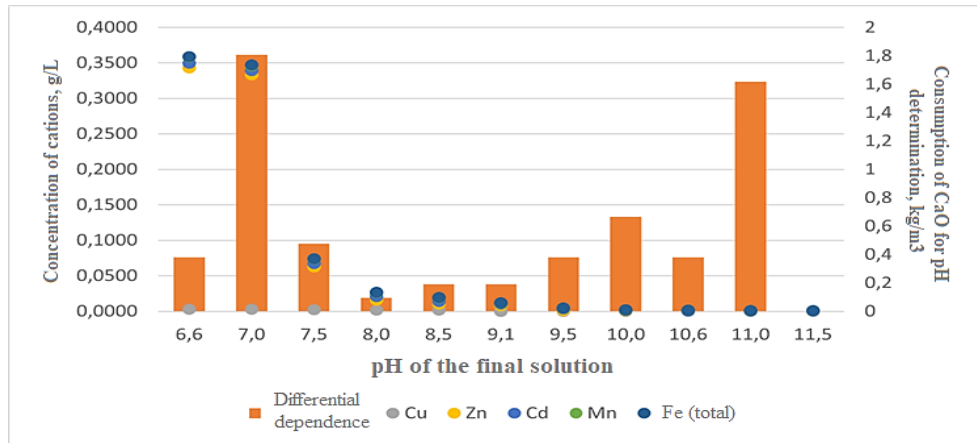


Figure 3. Lime consumption and concentrations of metal cations after treatment

Table 10 presents a comparison of the results achieved using the model mixture with the standard requirements [Ошибка! Источник ссылки не найден.].

Table 10. Achievement of target indicators

Final pH	Element, mg/L						
	Cu	Zn	Cd	Mn	Ca	Fe (total)	S(SO4)
less than 6.6	56.0**	480.0**	6.60**	8.40**	240**	1.00*	2200**
6.6	3.1**	340.0**	6.60**	8.40**	330**	0.99*	2100**
7.0	2.9**	330.0**	6.20**	6.90**	320**	0.87*	2100**
7.5	2.4**	60.0**	5.20**	6.00**	420**	0.75*	2000**
8.0	1.8**	14.0**	4.80**	5.70*	440**	0.65*	1900**
8.5	1.4**	8.8**	3.60**	5.30*	460**	0.60*	2200**
9.1	0.1*	7.8**	2.40**	1.10*	440**	0.51*	1900**
9.5	0.1*	1.2*	2.30**	0.90*	440**	0.46*	2200**
10.0	0.1*	0.1*	8.0**	0.85*	430**	0.32*	2400**
10.6	0.1*	0.1*	4.0*	0.80*	440**	0.12*	2100**
11.0	0.1*	0.1*	0.10*	0.70*	490**	0.09*	1900**
11.5	0.1*	0.1*	0.10*	0.50*	540**	0.01*	2200**
Standard	0.00078	0.0031	0.00065	0.0062	147.81	0.011	122.89
Clarks of river water (dissolved form) [14]	0.007	0.02	0.0002	0.01	12	0.04	3.8

* – Concentrations that meet regulatory requirements
 ** – Concentrations that do not meet regulatory requirements

As can be seen from the data in Table 12, at any pH value for heavy metals, manganese, calcium and sulfate sulfur, it is impossible to achieve standard indicators at existing treatment fa-

cilities, therefore it is necessary to establish such concentrations at the outlet of treatment facilities that will be safe primarily for the receiving reservoir.

It should be noted that the standards proposed to the enterprise by state regulatory authorities are significantly lower than the clarks of river water. The question arises regarding the environmental and economic efficiency of establishing such strict standards. It is well known that as the efficiency of cleaning increases, the costs of its implementation increase disproportionately, without bringing a significant environmental effect.

At the same time, if a significant decrease in their content in the treated water is observed for heavy metal ions, then for such indicators as Ca and $S_{(SO_4)}$ the concentrations established in the regulatory documentation are under no circumstances achieved. Moreover, the calcium content increases for objective reasons since this is an indicator of effective removal of metals.

For other regulated substances - saline ammonium, nitrites, nitrates, petroleum products and chlorides, purification by the physical and chemical method is impossible at existing treatment facilities. Therefore, standardization of the efficiency of treatment facilities based on these indicators is not carried out.

Conclusion. The work presents the results of laboratory studies to determine the optimal pH values that provide the maximum degree of purification for the specific conditions of the Irtysh mine. The experimental data obtained on model solutions were confirmed by the precipitation of metals from real mine water.

It has been determined that continuous pH monitoring using equipment is necessary to ensure optimal lime cleaning conditions.

Based on the conducted research, the following conclusions can be drawn:

1) Since in the process of lime cleaning heavy metals are extracted from mine waters under the influence of lime milk in the form of hydroxides, as a result of treatment, the concentration of calcium in the purified water increases.

2) The completeness of extraction of heavy metals from water by precipitation of their hydroxides depends on the pH value. Each metal is characterized by a certain pH range, which determines the completeness of precipitation.

3) Theoretical calculations have shown that, in accordance with solubility products, even if the required pH values are achieved, a situation arises in which one or more metals are deposited quite completely in the selected pH range, while for others in this range the required completeness of precipitation is not achieved. Laboratory studies have confirmed that deep purification of mine water is in the pH range of 9.5–10.5, but even in this case it is impossible to achieve the established standards.

4) – “the value of the permissible discharge standard must ensure compliance with the relevant environmental standards for water quality at the control site”.

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