EFFECT OF TEMPERATURE ON HYDROMETALLURGICAL REDUCTIVE-LEACHING OF ZINC CAKES

Khojiev Shokhrukh Toshpulatovich
Almalyk State Technical Institute, PhD, Associate Professor, Almalyk, Uzbekistan
E-mail: shohruhhojiyev@gmail.com
Kholikulov Doniyor Bakhtiyorovich
Almalyk State Technical Institute, DSc, Professor, Almalyk, Uzbekistan
E-mail: Kholikulov.d@tdtuof.uz
Khaydaraliev Kholbay Rustam o'g'li
Almalyk State Technical Institute, Basic Doctoral Student (PhD Candidate), Almalyk, Uzbekistan
E-mail: xolboyxaydaraliyev@gmail.com

Abstract. This paper investigates the technology of processing zinc cakes generated during zinc production by hydrometallurgical reductive-selective leaching. The effect of temperature on the leaching process was studied, and optimal technological conditions were determined. Sulfuric acid was used as the leaching agent, while hydrazine sulfate served as the reducing agent. According to laboratory experiments, the degree of zinc dissolution into the solution was analyzed within the temperature range of 25–55 °C, reaching a maximum of 94–98% at 55 °C. The dissolution degree of iron ranged from 13% to 24%, confirming the high selectivity of the process. Based on the obtained results, the optimal temperature for zinc cake processing was determined to be within 45–55 °C. The findings have practical significance for the cost-effective recycling of zinc production waste and for reducing metal losses during processing.

Keywords: zinc cake, hydrometallurgy, selective leaching, hydrazine sulfate, sulfuric acid, leaching temperature, metal recovery, selectivity, optimization.

Annotatsiya. Ushbu maqolada rux ishlab chiqarish jarayonida hosil bo'ladigan keklarni gidrometallurgik tiklovchi-tanlab eritish orqali qayta ishlash texnologiyasi tadqiq qilindi. Tadqiqotda eritish jarayoniga haroratning ta'siri o'rganilib, optimal texnologik sharoitlar aniqlangan. Erituvchi sifatida sulfat kislotasi, qaytaruvchi sifatida esa gidrazin sulfat qo'llanildi. Laboratoriya tajribalari natijalariga ko'ra, ruxni eritmaga o'tish darajasi 25–55 °C harorat oralig'ida tahlil qilindi va 55 °C da maksimal 94–98 % rux ajralishi qayd etildi. Temirning eritmaga o'tish darajasi esa 13–24 % ni tashkil etdi, bu esa tanlab eritish jarayonining samaradorligini tasdiqlaydi. Olingan natijalar asosida rux keklarini qayta ishlashda optimal harorat 45–55 °C deb topildi. Mazkur tadqiqot natijalari rux ishlab chiqarish chiqindilarini iqtisodiy jihatdan samarali qayta ishlash va metallarning yo'qotilishini kamaytirish uchun amaliy ahamiyatga ega.

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Kalit so‘zlar: rux keki, gidrometallurgiya, tanlab eritish, gidrazin sulfat, sulfat kislotasi, eritish harorati, metall ajralishi, selektivlik, optimallashtirish.

Аннотация. В данной статье исследована технология переработки цинковых кеков, образующихся в процессе производства цинка, методом гидрометаллургического восстановительно-избирательного выщелачивания. В ходе исследования изучено влияние температуры на процесс выщелачивания и определены оптимальные технологические условия. В качестве выщелачивающего реагента использовалась серная кислота, а в качестве восстановителя — гидразин сульфат. По результатам лабораторных экспериментов установлено, что степень перехода цинка в раствор была проанализирована в температурном диапазоне 25–55 °C и достигала максимального значения 94–98 % при 55 °C. При этом степень перехода железа в раствор составила 13–24 %, что подтверждает эффективность избирательного выщелачивания. На основании полученных данных оптимальная температура переработки цинковых кеков определена в пределах 45–55 °C. Полученные результаты имеют практическое значение для экономически эффективной переработки отходов цинкового производства и снижения потерь металлов.

Ключевые слова: цинковый кек, гидрометаллургия, избирательное выщелачивание, гидразин сульфат, серная кислота, температура выщелачивания, извлечение металлов, селективность, оптимизация.

Introduction.

In the field of metallurgy, zinc metal (Zn) is one of the most important and valuable materials widely used for corrosion protection, galvanization, construction, transportation, electrical equipment, and various other industrial sectors [1]. Due to its additional protective function in the iron and steel industries, as well as its role in chrome–nitrogen alloys, zinc concentrates, and stable production processes, global demand for zinc continues to grow steadily. In particular, countries with rapidly developing construction and transportation infrastructures are showing an increasing demand for zinc [2].

Several key factors act as major drivers of the global rise in zinc demand: construction activity, the need for galvanic coatings in the automotive and transportation industries, as well as recycling and waste recovery processes — all of which contribute to the growing consumption of zinc [3]. For instance, according to the International Zinc Association, construction and steel protection (galvanization) account for approximately 60% of total zinc consumption [4].

The price dynamics of zinc also significantly influence the demand-supply balance. For example, globally, the price of zinc metal on the London Metal Exchange (LME) has reached around USD 3,000 per ton [5].

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As seen from Figures 1, 2, and 3, the price of zinc has shown significant fluctuations over the past five years. Factors such as growing demand, supply constraints, global economic changes, and insufficient recycling of metal waste have all contributed to both the rise and fall of zinc prices [6].

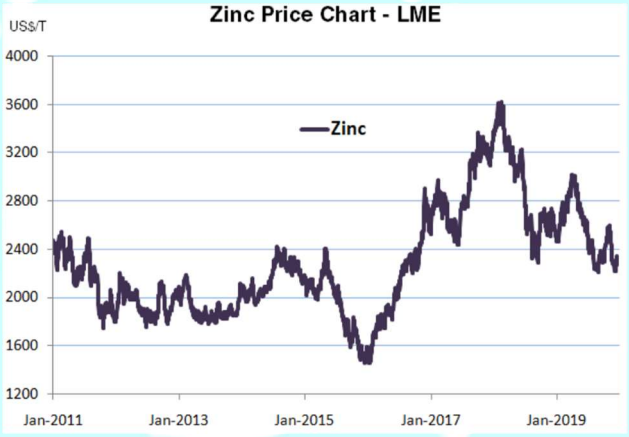


Fig.1. Zinc price chart - LME

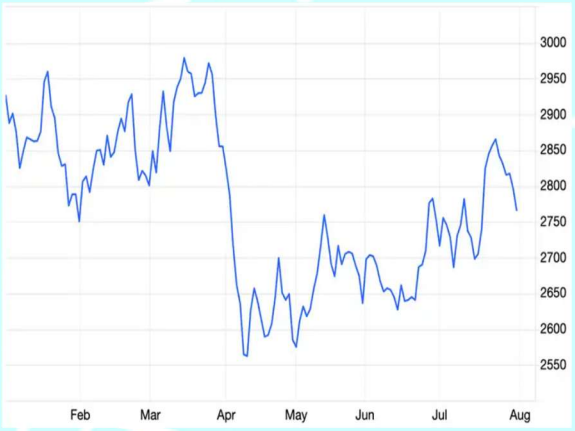


Fig.2. Zinc price, January 1 to July 31, 2025

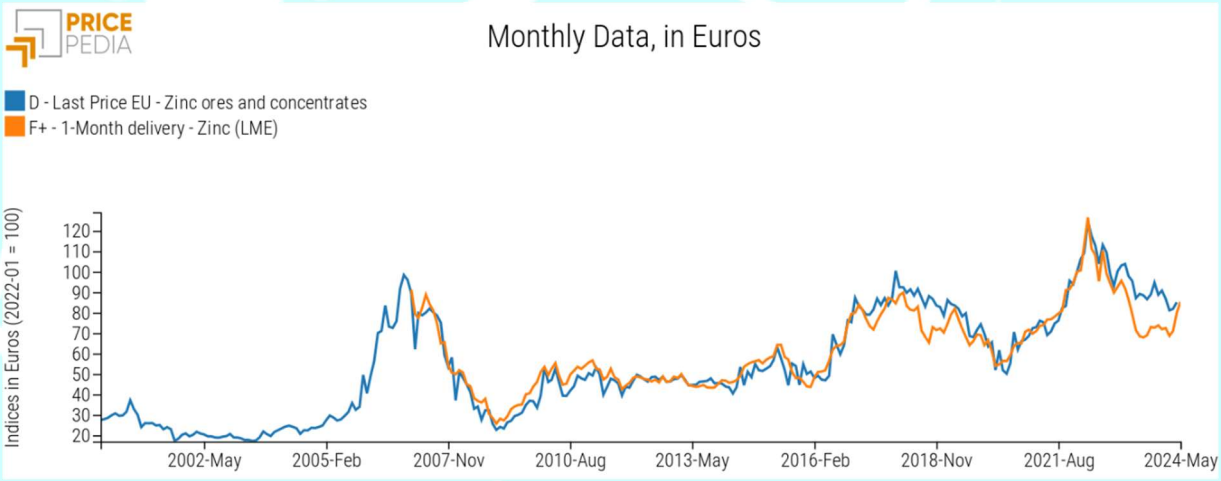


Fig.3. Financial Benchmarks for Zinc Prices

For instance, according to Trading Economics [7]:

➢ In October 2025, the price of zinc was approximately USD 3,023.60 per ton.

➢ In 2024, it was around USD 2,732 per ton.

The main factors influencing zinc price fluctuations include the following:

▪Supply-side changes: Issues in zinc ore mining and processing can affect the balance of supply.

▪Global economic conditions: Infrastructure development, automotive production, and the construction industry stimulate zinc consumption.

▪Recycling and waste recovery levels: Limited ability to extract zinc from technogenic (industrial) wastes can drive prices upward.

▪Inventories and stock levels: For example, declining zinc reserves in LME warehouses have exerted upward pressure on prices.

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On a global scale, the annual production of refined zinc metal in recent years has been approximately 13–14 million tons. In 2023, global refined zinc production was estimated at about 13.8 million tons [8].

In terms of ore mining, zinc also occupies a significant position — approximately 13 million tons of zinc are mined annually from underground deposits [9].

The major producing countries include China, Peru, and Australia, which hold large reserves and are considered global leaders. According to data from the Top 20 Zinc-Producing Countries, in 2024, China remained the largest producer with about 4,000,000 tons. Thus, maintaining a balance between production and consumption, as well as mitigating supply-chain constraints, has a substantial impact on zinc prices [10].

In Uzbekistan, zinc production and domestic demand for zinc are also highly relevant topics. The Almalyk Mining and Metallurgical Combine (AMMC) is a major metallurgical enterprise equipped with zinc production and processing facilities [11].

At AMMC, the zinc production process — from ore extraction to metal recovery — consists of several stages: roasting → leaching → electrolysis → remelting of cathode zinc. According to available data, AMMC aims to increase zinc metal output from approximately 78,000 tons to 120,000 tons [12].

Moreover, AMMC's 2023 performance reports indicate that the production plan for zinc metal from local raw materials was fulfilled by about 101.8%, while the overall growth rate was around 87.3%. As the metallurgy, galvanization, construction, and transportation sectors continue to develop in Uzbekistan, the domestic demand for zinc is expected to rise further [13].

This trend underscores the importance of expanding zinc production capacity and recovering zinc from technogenic wastes [14]. For Uzbekistan, utilizing polymetallic waste and secondary resources as an additional source of zinc supply holds strategic importance. Without the involvement of such resources, the country risks increasing dependence on imports and facing challenges in meeting internal demand [15].

A considerable amount of zinc accumulates in metallurgical process residues such as cakes, tailings, and other oxide and sulfide wastes [16]. Failing to process these wastes is economically inefficient and environmentally problematic. Therefore, rational utilization of technogenic sources provides significant opportunities to strengthen the country's domestic zinc supply, reduce import volumes, and enhance overall production efficiency [17].

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Such an approach not only transforms existing waste into economically valuable resources, but also allows for the generation of added value through the recovery of raw materials from zinc-bearing materials [18].

Materials and Methodology. The object of this study is the zinc cake (final solid residue) generated during the metallurgical processes at Almalyk Mining and Metallurgical Combine JSC (AMMC). This residue is mainly formed during the leaching stage of roasted zinc concentrate with sulfuric acid solution following the oxidation process [19].

According to analytical data, the zinc cake contains significant amounts of zinc, iron, copper, cadmium, sulfur compounds, and other associated metal components. For instance, modern analyses have shown that the total zinc content in the zinc cake is approximately 21%, copper is about 2–3%, and iron is around 15%.

From a mineralogical perspective, the primary phases identified in the zinc cake include:

- Sphalerite (ZnS),
- Zinc ferrite ($ZnFe_2O_4$),
- Copper ferrite ($CuFe_2O_4$),
- Metal silicates,
- Copper sulfate,
- Zinc sulfate,
- Gypsum ($CaSO_4 \cdot 2H_2O$), and other compounds.

For compositional analysis, the following instrumental methods were applied:

a. Spectrometry for chemical composition,
b. X-ray diffraction (XRD), and
c. Scanning electron microscopy (SEM) with energy-dispersive X-ray (EDX) analysis.

The experimental methodology was organized as follows:

1. Sulfuric acid was selected as the leaching medium.
2. Within the framework of reductive–selective leaching, one of the most effective reducing agents — hydrazine sulfate — was used. The process aimed to minimize the dissolution of accompanying metals into the leach solution.
3. Experiments were conducted under varying conditions of temperature, acid concentration (M), solid-to-liquid ratio (S/L, g/ml or g/g), and leaching time (hours). In experiments №1–25 (as shown in your data tables), these parameters (acid concentration, leaching time, temperature, and S/L ratio) were chosen as variable factors.

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4. After each experiment, the concentrations of zinc (Zn), copper (Cu), cadmium (Cd), and iron (Fe) in the leach solution were determined, and the percentage of metal dissolution was calculated.

5. Based on the obtained data, the optimal leaching conditions were established, targeting maximum zinc extraction (≥ 90%) and minimum iron dissolution (≤ 30%).

Results and Discussion. Improving the efficiency of zinc cake recycling and ensuring the maximum recovery of valuable metals represent one of the most relevant challenges in modern hydrometallurgy. The primary goal of the technological process is to maximize the dissolution of zinc, the main valuable component of the cake, while minimizing the dissolution of accompanying elements such as copper, cadmium, and iron in the leach solution.

In this study, a series of laboratory experiments were conducted to optimize the hydrometallurgical processing technology of zinc cakes. The main factors influencing the leaching process — sulfuric acid concentration, leaching time, temperature, and solid-to-liquid ratio (S/L) — were selected as variables. During the experiments, the concentrations of zinc (Zn), copper (Cu), cadmium (Cd), and iron (Fe) transferred into the leach solution were measured, and based on these data, the optimal technological conditions were determined.

To achieve this, a number of large-scale experimental trials were carried out under various conditions, and the obtained results are presented in Table 1.

Table 1.

Results of reductive–selective leaching of zinc cake under various experimental conditions

№	Sulfuric acid concentration (M)	Leaching time (hours)	Leaching temperature (°C)	Solid-to-liquid ratio (S/L, g)	Zinc dissolution into solution (%)	Copper dissolution into solution (%)	Cadmium dissolution into solution (%)	Iron dissolution into solution (%)
1	2,0	2,0	55,0	8,0	82,6	86,6	83,1	48,5
2	2,0	2,0	55,0	2,0	69,3	73,9	48,9	26,7
3	2,0	6,0	55,0	8,0	94,6	38,9	99,2	23,5
4	2,0	6,0	55,0	8,0	95,5	96,7	32,6	36,6
5	2,0	4,0	25,0	2,0	79,6	85,6	94,8	22,9
6	3,0	2,0	25,0	8,0	78,6	84,8	72,8	16,2
7	3,0	4,0	25,0	2,0	79,6	79,8	47,6	21,6
8	3,0	6,0	25,0	8,0	80,6	87,5	81,0	13,4

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9	3,0	4,0	55,0	2,0	88,8	95,0	80,1	23,4
10	3,0	6,0	55,0	8,0	98,4	89,9	94,8	43,4
11	5,0	2,0	55,0	8,0	95,5	96,7	32,6	36,6
12	5,0	4,0	55,0	2,0	71,6	80,2	47,6	21,6
13	5,0	6,0	55,0	8,0	95,5	96,7	32,6	36,6
14	5,0	4,0	25,0	2,0	78,6	84,8	72,8	16,2
15	5,0	6,0	25,0	8,0	80,6	87,5	81,0	13,4
16	2,0	2,0	55,0	14,0	75,9	15,3	96,8	16,1
17	2,0	4,0	25,0	14,0	73,9	79,8	99,0	24,2
18	3,0	2,0	55,0	8,0	82,5	86,6	83,1	48,5
19	3,0	4,0	25,0	8,0	88,8	95,0	80,1	23,4
20	5,0	2,0	55,0	8,0	80,6	87,5	81,0	13,4
21	2,0	6,0	25,0	8,0	94,5	38,9	99,2	23,5
22	3,0	6,0	55,0	8,0	80,6	87,5	81,0	13,4
23	5,0	6,0	25,0	8,0	80,6	87,5	81,0	13,4
24	2,0	2,0	55,0	8,0	82,5	86,6	83,1	48,5
25	3,0	2,0	25,0	8,0	78,6	84,8	72,8	16,2

Considering that the main objective of the large-scale industrial pilot experiment was to achieve maximum zinc dissolution (≥90%) and minimum iron dissolution (≤30%) from the zinc cake, the results presented in Table 1 show that many experiments yielded high zinc extraction rates in the range of 94.5–98.4%, indicating excellent process efficiency.

For copper (Cu) and cadmium (Cd), in some cases (for example, at 2M acid concentration and 2 hours of leaching), the concentration of copper in the solution was relatively low. This suggests that copper dissolution strongly depends on key factors such as acid strength and leaching duration.

As for iron (Fe), in many experiments its transfer to the solution remained low (13–24%), which demonstrates that the selective leaching mechanism functioned effectively.

The influence of temperature on the selective leaching process of zinc cake in the presence of hydrazine as a reducing agent and sulfuric acid solution was analyzed (see Figure 4).

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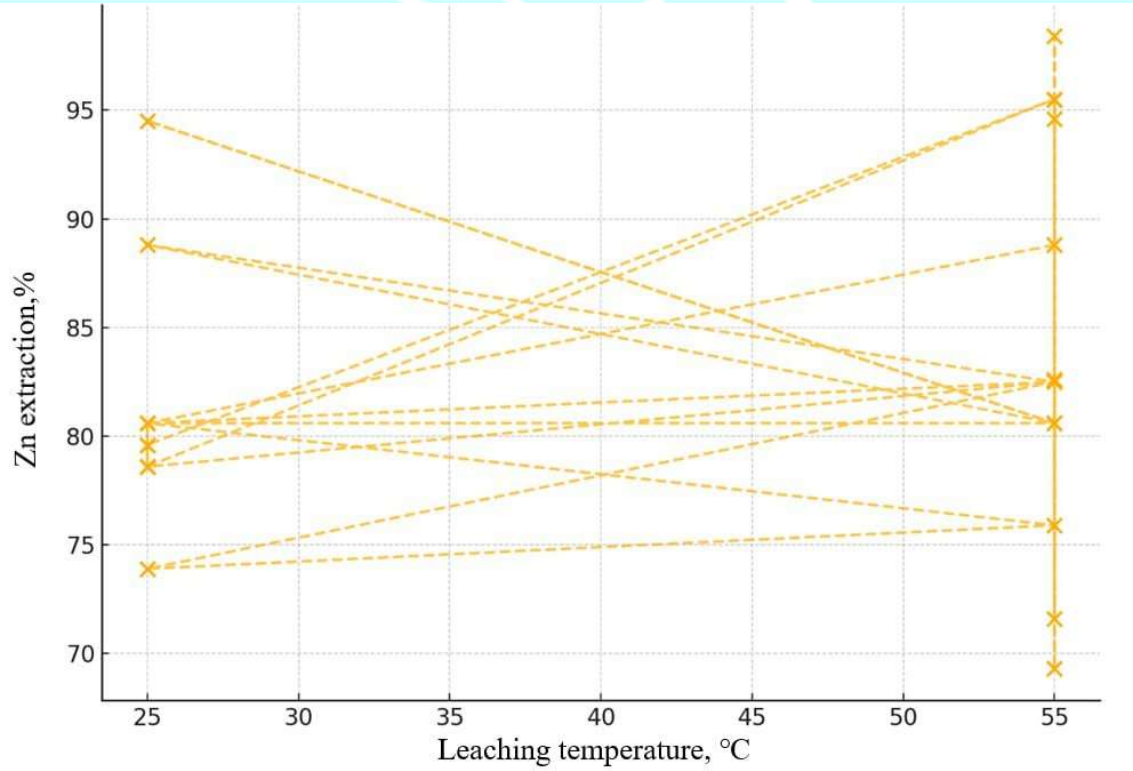


Fig. 4. Dependence of zinc dissolution percentage on leaching temperature

Overall, as the temperature increases, the percentage of zinc passing into the solution steadily rises to a higher level. From the graph shown in Figure 4, it can be observed that the maximum dissolution of Zn occurs at around 55 °C (94–98%). At lower temperatures (25 °C), the percentage of Zn leached into the solution is slightly lower (78–88%). This graph confirms the optimal temperature range to be 25–55 °C.

At higher temperatures, however, energy consumption increases, the rate of water evaporation from the solution also rises, while the efficiency improves only slightly.

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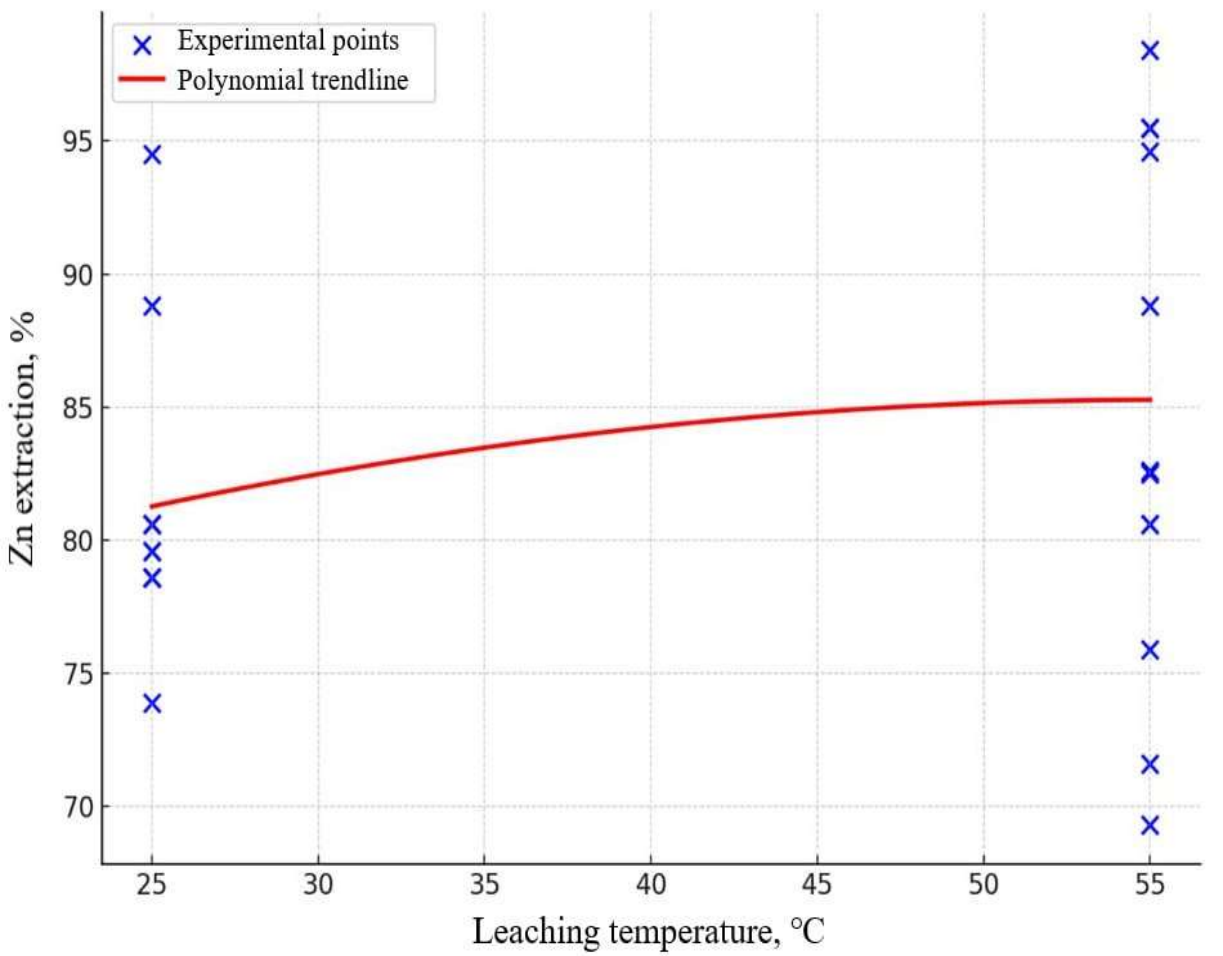


Fig. 5. Dependence of Zinc Dissolution on Temperature (with Trend Line)

In Figure 5, the dependence of zinc dissolution on temperature is presented with a trend line (polynomial regression). The mathematical expression of the trend line is given as follows:

Polynomial (2nd-degree) regression equation:

$$Zn(\%) = -0.00435 \times T^2 + 0.4817 \times T + 71.95$$

where:

T — leaching temperature (°C),

Zn(%) — percentage of zinc dissolved into the solution.

The presence of a negative coefficient for T^2 (−0.00435) indicates that as the temperature increases, zinc dissolution initially rises but then slows down or may even decrease after a certain temperature threshold. This is important in determining the "optimal temperature range" in industrial processes.

As shown in the graph, the zinc dissolution rate increases within the temperature range of 25–55 °C, after which it gradually levels off or slightly declines. Therefore, the optimal leaching temperature is around 45–55 °C, since higher temperatures do not lead to further improvement in efficiency.

Conclusion. The results of the conducted studies revealed that temperature is a key influencing factor in the hydrometallurgical reductive-selective leaching

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process of cakes generated during zinc production. Experiments carried out in sulfuric acid solution with the addition of hydrazine sulfate demonstrated that as the leaching temperature increases, the degree of zinc dissolution rises, reaching a maximum value of 94–98% at 55 °C.

At lower temperatures (25 °C), the zinc dissolution rate ranged from 78–88%, which is attributed to kinetic limitations of the process. However, at temperatures above 55 °C, energy consumption increases while the improvement in efficiency remains relatively small.

Additionally, the results showed that the degree of iron dissolution is within 13–24%, which indicates the high selectivity of the selective leaching mechanism.

Thus, for the hydrometallurgical processing of zinc cakes, the optimal technological conditions are recommended as follows: 3 M sulfuric acid concentration, 6-hour leaching time, and a temperature range of 45–55 °C. Under these conditions, maximum zinc dissolution and minimum iron dissolution are achieved.

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