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DEVELOPMENT OF A COMPREHENSIVE SOFTWARE SOLUTION FOR PROCESSING HIGH-SULFUR, COPPER-POOR CONCENTRATES IN THE COPPER SMELTING INDUSTRY

Abstract: *The depletion of high-grade copper ores and the increasing prevalence of low-grade, high-sulfur copper concentrates present significant challenges to the copper smelting industry. Traditional smelting processes struggle to maintain economic viability and comply with environmental regulations when processing these complex ores. This paper details the development of a comprehensive software solution designed to simulate the smelting process for high-sulfur, copper-poor concentrates. The software employs a detailed mathematical model to predict the yields and compositions of products, including valuable metals, during the smelting process. It integrates multiple modules, such as ore input, smelting simulation, and results presentation, providing a user-friendly platform for optimizing smelting operations. Critical parameters like ore composition, smelting temperature, and flux addition are incorporated into the model, enabling accurate predictions of matte and slag outputs. By analyzing these outputs, the software aids in optimizing metal recovery and reducing losses, ultimately enhancing the efficiency and sustainability of copper production. This tool is particularly relevant for large sulfide copper ore deposits, such as those in Kazakhstan, which have high sulfur content and low copper levels. The software's ability to simulate different processing scenarios provides valuable insights for industrial applications, supporting the development of more efficient and eco-friendly smelting technologies. The comprehensive software solution not only addresses the technical challenges of processing high-sulfur, low-copper ores but also contributes to the industry's efforts to reduce environmental impact and improve resource management. This innovation represents a significant step forward in the optimization of copper smelting operations, promoting sustainability and efficiency in the face of declining ore quality.*

Key words: *copper smelting, high-sulfur ores, smelting simulation, metal recovery, optimization.*

Introduction

The copper smelting industry is transforming due to the depletion of high-grade ores and the rise of complex, low-grade ores [1, 2]. These ores, high in sulfur and low in copper, challenge traditional smelting processes [3-5]. Efficient processing of these concentrates is crucial for maintaining economic viability and adhering to environmental regulations. The volume of industrial waste from traditional smelting is comparable to copper deposit reserves, driving the need for more efficient and eco-friendly technologies [6-8]. Efficient recovery of valuable metals and reduction of metal losses in smelting slags are key aspects of processing these ores [4, 5]. Developing new technologies for high-sulfur, copper-poor concentrates is essential to address these challenges and optimize copper production efficiency.

Researchers are exploring various methods to address issues related to complex ores. High-temperature processes for the direct reduction of copper slag are being investigated for their environmental friendliness and waste-free nature [9-11], aiming to extract valuable metals from slag and minimize environmental impact. High-temperature processes reduce waste but face scalability issues due to high energy demands, especially with sulfur-rich, copper-poor ores.

Technologies for reducing metal losses during copper smelting have seen advancements. Komkov et al. [12] developed a thermodynamic model for impurity distribution during smelting in the Vanyukov furnace, showing how temperature and composition influence metals like zinc and lead between matte, slag, and gases. Kenzhaliev et al. [13] focused on minimizing copper losses in slag at the Balkhash smelter, demonstrating how raw material composition affects smelting efficiency. Mamonov et al. [14] improved slag processing with slow cooling and ultrafine grinding, enhancing copper recovery. Additionally, flotation enrichment techniques have been developed to separate valuable metals from converter and waste slags, although challenges remain with sulfur-rich, low-copper ores [15].

However, flotation enrichment struggles with high sulfur, low copper ores, and its energy costs from ultrafine grinding raise concerns about long-term viability. Innovative technologies involving slow cooling and ultrafine grinding of slag are also being explored to significantly improve flotation and produce copper-rich concentrates [16-18]. While slow cooling and ultrafine grinding improve recovery, they add significant energy and time costs, requiring a detailed cost-benefit analysis.

The industrial development of large Boshchekul and Aktogay deposits of sulfide copper ores in Kazakhstan highlights the need for further research and development [19]. Copper concentrates from these deposits have high sulfur content and low copper levels, requiring tailored processing methods [20]. Determining the properties of resulting slag is critical for optimizing the smelting process and minimizing metal losses

This paper presents a software solution designed to address these challenges by simulating the smelting process for high-sulfur, copper-poor concentrates. The software utilizes a comprehensive mathematical model that incorporates key parameters influencing smelting efficiency and accurately predicts product yields and material flows. The software provides a valuable tool for optimizing smelting operations, reducing metal losses, and improving overall efficiency.

Methods and Materials

This part outlines the computational processes used to calculate the chemical composition of alloys derived from multiple ores. The system involves selecting ores, initializing their compositions, calculating the total weights and percentages of each element, and determining the concentrations of elements in both stein (the metal product) and slag (the byproduct). By systematically processing the input data through these computational steps, the model accurately predicts the distribution of elements in the final products, thereby enabling informed conclusions about smelting efficiency and metal recovery.

2.1 Ore Selection and Data Initialization

A variety of ores are selected based on their elemental compositions and weights, containing elements like Gold (Au), Silver (Ag), Silicon Dioxide (SiO_2), Calcium Oxide (CaO), Sulfur (S), Iron (Fe), Copper (Cu), Aluminum Oxide (Al_2O_3), and Arsenic (As). The software requires input of gold (Au) and silver (Ag) concentrations in grams per tonne of ore. Other elements (e.g., Cu, Fe, S, SiO_2, CaO) are input as weight percentages, converted to absolute weights based on the total ore weight. All weights are standardized to grams per ton. The total weight of each element across all selected ores is then calculated by summing the individual weights from each ore. The copper and sulfur content of the ore are crucial inputs as they significantly influence the formation of matte, a copper-rich product.

For element percentages, the percentage of each element relative to the total weight of the alloy is calculated. For Au and Ag, these percentages are converted to parts per million (ppm). These processed input data are essential for accurately modeling the smelting process, as they directly impact the predicted concentrations of elements in the stein and slag.

2.2 Software Modules

The software consists of three modules:

2.2.1 **Ore input module**

This module allows users to input the chemical composition of the ore, including the weight percentages of various elements. Users can also specify the weight of the ore batch.

2.2.2 ***Smelting simulation module***

This module utilizes a comprehensive mathematical model to simulate the smelting process. It directly leverages the input data initialized in Section 2.1, such as elemental concentrations and ore weights, to inform the simulation parameters. The model incorporates key parameters influencing smelting efficiency, including the chemical composition of the ore, the smelting temperature, and the addition of fluxes. The model predicts the composition and yield of both matte and slag, as well as the distribution of valuable metals. This module implements the calculations described in the following sections:

Calculation of materials in stein

To calculate the concentrations of various materials in the stein (a metal product) and its total weight, several steps are followed. First, the amount of sulfur lost to gas is determined by applying the gas loss percentage to the total sulfur content. Next, the sulfur combined with copper to form copper sulfide is calculated using the ratio of copper to sulfur in copper sulfide. The sulfur in the stein is then found by subtracting the sulfur in copper sulfide from the sulfur lost to gas. The iron content in the stein is determined based on the sulfur present, using the ratio of iron to sulfur in iron sulfide. Finally, the weight of the stein is calculated by summing the total copper, sulfur in the stein, iron in the stein, and an additional factor for other materials.

Below, the formulae are described. Equation 1 shows the formula of Sulfur lost to gas, equation 2 shows the sulfur in copper sulfide, equation 3 shows the sulfur in stein, equation 4 shows Iron in stein and equation 5 shows the calculation of the weight of the stein.

$$\mathrm{Sulfur_{gas}} = \mathrm{Total\ Sulfur} \times \frac{100-\mathrm{GAS\ LOSS\ PERCENTAGE}}{100} \quad (1)$$

$$\mathrm{Sulfur_{CuS}} = \mathrm{Total\ Copper} \times \mathrm{COPPER\ TO\ SULFUR\ RATIO\ IN\ COPPER\ SULFIDE} \quad (2)$$

$$\mathrm{Sulfur_{stein}} = \mathrm{Sulfur_{gas}} - \mathrm{Sulfur_{CuS}} \quad (3)$$

$$Iron_{stein} = Sulfur_{stein} \times IRON\ TO\ SULFUR\ RATIO\ IN\ IRON\ SULFIDE \quad (4)$$

$$Weight_{stein} = Total\ copper + Sulfur_{stein} + Iron_{stein} + Other\ Materials\ Factor \times Total\ Other\ Materials \quad (5)$$

The sulfur in the stein ($Sulfur_{stein}$) is calculated by accounting for the sulfur that is not lost to gas and is not part of the copper sulfide. Iron in the stein ($Iron_{stein}$) is then determined using the iron to sulfur ratio in iron sulfide. The percentage of sulfur in the stein is found by dividing the sulfur gas by the weight of the stein and multiplying by 100. Similarly, the percentage of iron in the stein is determined by dividing the iron gas by the weight of the stein and multiplying by 100. The percentage of copper in the stein is calculated by dividing the total copper by the weight of the stein and multiplying by 100.

Calculation of Materials in Slag

The concentration of elements in the slag (byproduct) and the total weight of the slag are calculated by considering the concentrations of gold and silver in the stein and determining the total weight of the slag based on the iron oxide and other materials present. The formula for calculating gold concentration in the stein is given in equation 6. The weight of the slag is given in equation 7. The iron content that does not end up in the stein contributes to the iron content in the slag and is converted to iron oxide using a predefined ratio. Iron in slag is calculated by subtracting the iron in the stein from the total iron content. The iron oxide in slag is then calculated by multiplying the iron in slag by the iron oxide to iron rathistio in slag.

$$\mathrm{Gold\ Concentration_{stein}} = \frac{\mathrm{Total\ Gold}}{Weight_{stein}} \times \mathrm{GOLD\ RECOVERY\ EFFICIENCY} \times \mathrm{GOLD\ SILVER\ SCALE\ FACTOR} \quad (6)$$

$$\text{Weight}_{\text{slag}} = \text{Iron in Slag} + \text{Total Al}_2\text{O}_3 + \text{Total SiO}_2 + \text{Total CaO} + \text{Other Materials in Slag Factor} \times \text{Total Other Materials} \quad (7)$$

Final Calculation and Analysis

The total weight of the slag is calculated by summing the contributions of iron in the slag, Al_2O_3, SiO_2, CaO, and other materials. The percentage of each element in the slag is determined by dividing the weight of the element by the total weight of the slag and converting it to a percentage.

The smelting process involves several key constants: Gas Loss Percentage (sulfur lost as gas), Copper to Sulfur Ratio in Copper Sulfide, Iron to Sulfur Ratio in Iron Sulfide, Iron Oxide to Iron Ratio in Slag, Other Material Factor (additional materials in stein), Other Materials in Slag Factor, Gold Recovery Efficiency, Silver Recovery Efficiency, and Gold Silver Scale Factor (converts gold and silver concentrations from grams per ton to grams per tonne). These constants are used in the smelting simulation module to calculate element distribution in the matte and slag.

2.2.3 **Results Module**

This module presents the simulations results in a user-friendly table format, allowing users to analyze the impact of different process parameters on smelting efficiency and to identify potential areas of improvement.

2.3 Software Workflow

The software workflow for this methodology, as seen in figure 1, integrates the various mathematical calculations into a cohesive system that automates the entire process. Starting with the input data from ore selection and initialization (Section 2.1), the workflow systematically processes these inputs through the ore input module, smelting simulation module, and results module. Below is an explanation of the software's operation.

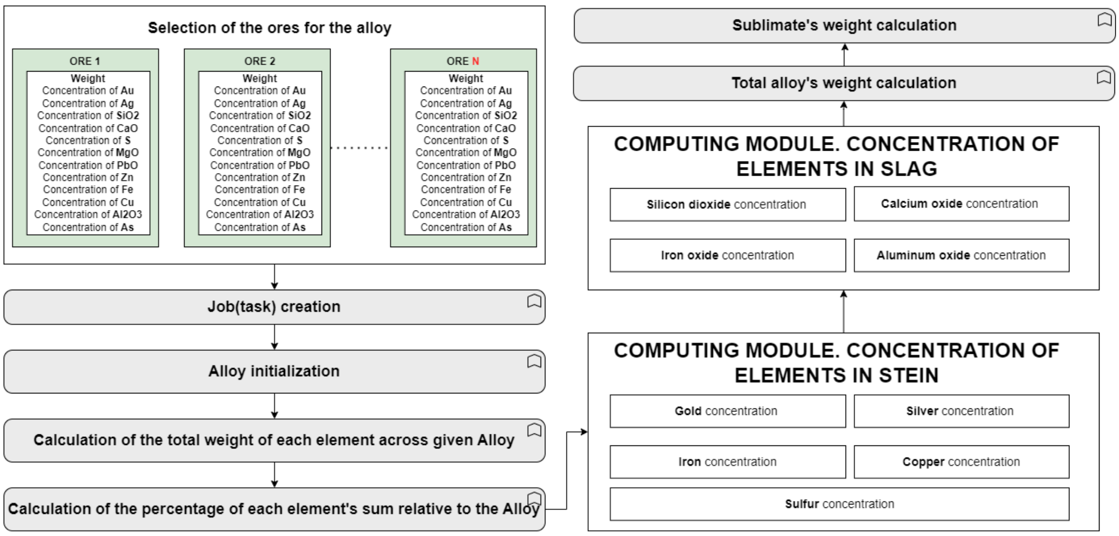


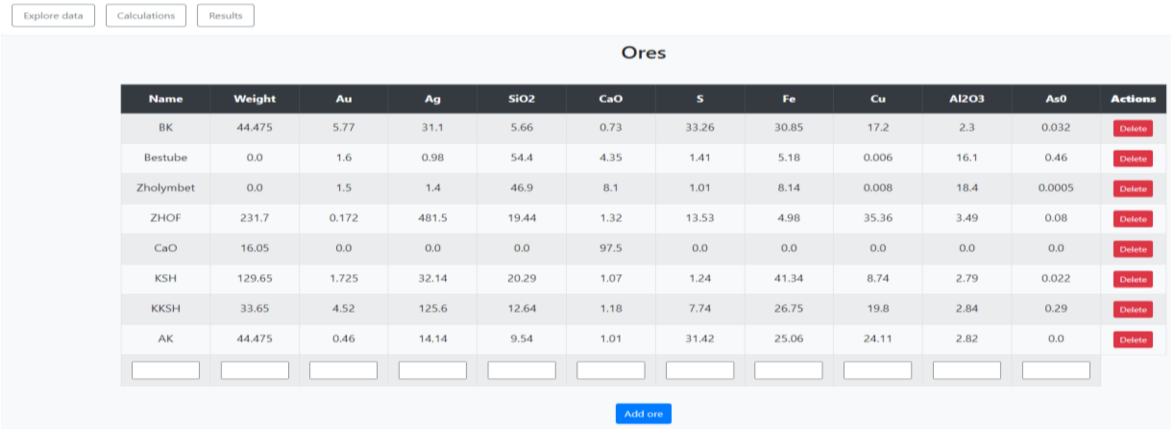
Figure 1 – Software Workflow for Calculating Chemical Composition of Alloys

First, the ores are selected, and their compositions and weights are inputted using the Ore Input Module. Each ore's data is captured and stored for further processing. Once the ores are selected, a new job is created by the software to manage the data. This job acts as a container for all the ore data and subsequent calculations. A Job object is created, and each selected ore is associated with this job through “OreJob” objects. Each selected ore is initialized as a compound object by the software, converting their elemental weights and concentrations into consistent units. This involves creating Compound objects, which handle the conversion of measurements.

Results

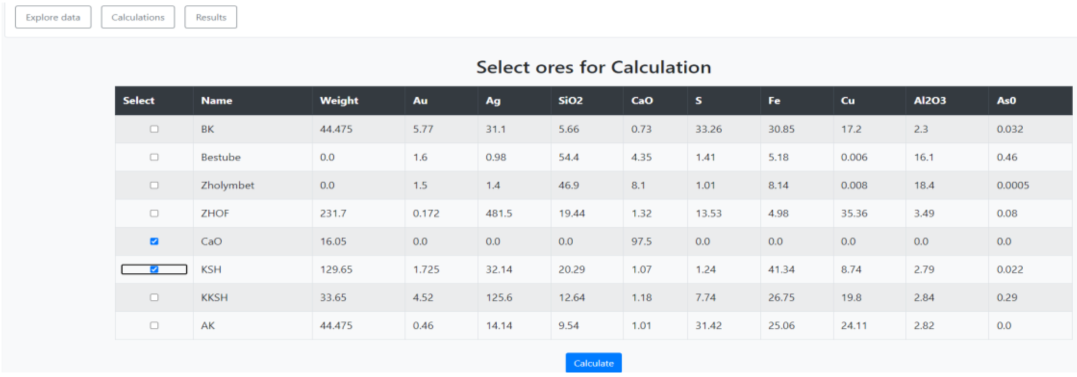
This section provides an overview of the data input process, the selection of ores for calculation, and the results of the smelting simulations, which include the concentrations of elements in both the stein and slag.

Figure 2 shows the interface for inputting the chemical composition and weights of various ores. Users can add new ores or delete existing ones. Each ore is listed with its name, weight, and concentrations of elements. Once the ores are inputted, users can select specific ores for the calculation. This selection process is crucial for creating a new job that will manage the data and perform the necessary calculations. In Figure 3, the CaO and KSH ores were selected for calculation for demonstration purposes.



Name	Weight	Au	Ag	SiO2	CaO	S	Fe	Cu	Al2O3	As0	Actions
BK	44.475	5.77	31.1	5.66	0.73	33.26	30.85	17.2	2.3	0.032	Delete
Bestube	0.0	1.6	0.98	54.4	4.35	1.41	5.18	0.006	16.1	0.46	Delete
Zholymbet	0.0	1.5	1.4	46.9	8.1	1.01	8.14	0.008	18.4	0.0005	Delete
ZHOF	231.7	0.172	481.5	19.44	1.32	13.53	4.98	35.36	3.49	0.08	Delete
CaO	16.05	0.0	0.0	0.0	97.5	0.0	0.0	0.0	0.0	0.0	Delete
KSH	129.65	1.725	32.14	20.29	1.07	1.24	41.34	8.74	2.79	0.022	Delete
KKSH	33.65	4.52	125.6	12.64	1.18	7.74	26.75	19.8	2.84	0.29	Delete
AK	44.475	0.46	14.14	9.54	1.01	31.42	25.06	24.11	2.82	0.0	Delete

Figure 2 – Ore Data Input

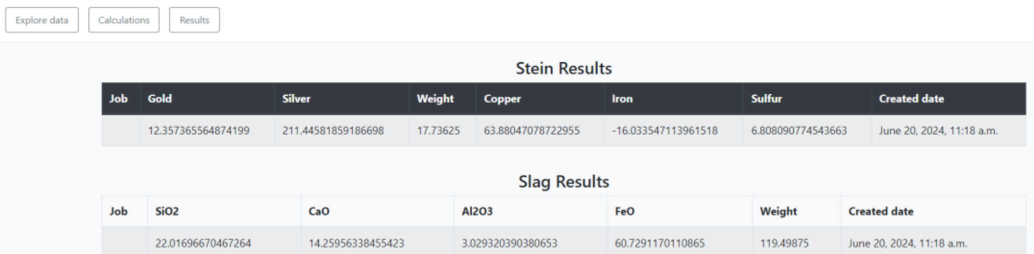


Select	Name	Weight	Au	Ag	SiO2	CaO	S	Fe	Cu	Al2O3	As0
☐	BK	44.475	5.77	31.1	5.66	0.73	33.26	30.85	17.2	2.3	0.032
☐	Bestube	0.0	1.6	0.98	54.4	4.35	1.41	5.18	0.006	16.1	0.46
☐	Zholymbet	0.0	1.5	1.4	46.9	8.1	1.01	8.14	0.008	18.4	0.0005
☐	ZHOF	231.7	0.172	481.5	19.44	1.32	13.53	4.98	35.36	3.49	0.08
☑	CaO	16.05	0.0	0.0	0.0	97.5	0.0	0.0	0.0	0.0	0.0
☑	KSH	129.65	1.725	32.14	20.29	1.07	1.24	41.34	8.74	2.79	0.022
☐	KKSH	33.65	4.52	125.6	12.64	1.18	7.74	26.75	19.8	2.84	0.29
☐	AK	44.475	0.46	14.14	9.54	1.01	31.42	25.06	24.11	2.82	0.0

Figure 3 – Ore Selection for Calculation

Once the user clicks on «calculate», the results of the smelting calculations are displayed, showing the concentrations of various elements in the stein (metal product) and slag (byproduct). The results include the job ID, concentrations of Au, Ag, Cu, Fe, and S in the stein, as well as Silicon Dioxide (SiO_2), Calcium Oxide (CaO), Aluminum Oxide (Al_2O_3), and Iron Oxide (FeO) in the slag. This is illustrated in Figure 4.

For ease of use and analytical purposes, a history of simulation is saved. As seen in Figures 5 and 6, a detailed view of the stein and slag results from multiple jobs is saved. Each row corresponds to a specific job, showing the concentrations, the total weight of the stein, Cu, Fe, and S, along with the creation date of each job.



Job	Gold	Silver	Weight	Copper	Iron	Sulfur	Created date
	12.357365564874199	211.44581859186698	17.73625	63.88047078722955	-16.033547113961518	6.808090774543663	June 20, 2024, 11:18 a.m.

Job	SiO2	CaO	Al2O3	FeO	Weight	Created date
	22.01696670467264	14.25956338455423	3.029320390380653	60.7291170110865	119.49875	June 20, 2024, 11:18 a.m.

Figure 4 – Calculation Results – Stein and Slag

Stein Results

Job	Gold	Silver	Weight	Copper	Iron	Sulfur	Created date
6	3.0295356914331295	489.90498313849855	224.06812500000004	52.79198011765395	14.579550304176466	21.529166631800038	June 13, 2024, 6:32 p.m.
8	7.002320339690937	34.66115132952805	35.915	21.30029235695392	44.730613949603224	30.885423917583182	June 13, 2024, 7:03 p.m.
9	0.3165644856025451	813.853938276358	123.3725	66.4086404993009	4.2979594318020595	19.05813694299783	June 13, 2024, 10:34 p.m.
14	12.427433553051243	212.64474590686797	17.63625	64.24268197604366	-16.12445956481678	6.846693599829896	June 13, 2024, 10:35 p.m.
15	12.929072102352814	329.94001951642633	11.528749999999999	57.768621923452244	4.326141168817086	16.91423614875854	June 13, 2024, 10:35 p.m.
16	0.564521390233172	15.936333655961286	35.515625	30.183897932248133	38.42146942366916	29.501099868015835	June 13, 2024, 10:35 p.m.
17	7.002320339690937	34.66115132952805	35.915	21.30029235695392	44.730613949603224	30.885423917583182	June 13, 2024, 10:36 p.m.
19	6.982877551020406	34.56491045397751	36.015	21.241149521032902	44.60641399416909	30.799666805497704	June 19, 2024, 4:54 p.m.
20	12.357365564874199	211.44581859186698	17.73625	63.88047078722955	-16.033547113961518	6.808090774543663	June 20, 2024, 11:18 a.m.

Figure 5 – Detailed Stein Results

Slag Results

Job	SiO2	CaO	Al2O3	FeO	Weight	Created date
6	35.09880328039144	9.064491813670784	6.3668785940875186	36.350315303711696	234.65187499999996	June 13, 2024, 6:32 p.m.
8	67.56032171581764	8.57908847184986	27.34584450402143	-80.8310991957103	3.730000000000003	June 13, 2024, 7:03 p.m.
9	51.36714851880363	3.489863997947139	9.226470504376586	9.146229700502223	87.6825	June 13, 2024, 10:34 p.m.
14	25.383808294841952	1.341067789047142	3.492565033345795	70.01583300742722	103.64875	June 13, 2024, 10:35 p.m.
15	22.425961348196026	2.1106787151243322	5.0656289162983965	57.67523815805592	18.95125	June 13, 2024, 10:35 p.m.
16	88.52929662012265	9.395797990343205	26.099438862064456	-66.99539531328644	4.7893750000000015	June 13, 2024, 10:35 p.m.
17	67.56032171581764	8.57908847184986	27.34584450402143	-80.8310991957103	3.730000000000003	June 13, 2024, 10:36 p.m.
19	12.870275791624106	81.56281920326863	5.209397344228805	-15.398365679264536	19.580000000000002	June 19, 2024, 4:54 p.m.
20	22.01696670467264	14.25956338455423	3.029320390380653	60.7291170110865	119.49875	June 20, 2024, 11:18 a.m.

Figure 6 – Detailed Slag Results

Discussion

The results demonstrate the effectiveness of the software in managing and processing complex chemical data to predict the composition and yield of both the stein and slag. By accurately utilizing the input data – such as elemental concentrations and ore weights – the mathematical model effectively simulates the smelting process under various conditions. The detailed tables and figures allow for thorough analysis of how different input parameters influence smelting outcomes, enabling users to optimize the composition of alloys and improve smelting efficiency. Each job's results provide insights into the distribution of valuable metals and the effectiveness of the smelting parameters used.

By providing a clear and organized interface for inputting data and selecting ores, the software simplifies the process of running smelting simulations. The ability to save and review the history of simulations allows users to track changes and improvements over time. The detailed output of elemental concentrations in both the stein and slag enables users to fine-tune the smelting process, thereby maximizing metal recovery and minimizing waste.

Overall, the software proves to be a valuable tool for the copper smelting industry, providing crucial insights into the smelting process and helping to optimize operations for better efficiency and sustainability.

Conclusion

The development of a comprehensive software solution for processing high-sulfur, copper-poor concentrates in the copper smelting industry addresses a critical challenge due to the depletion of high-grade ores and the rise of complex low-grade ores. These ores, rich in sulfur but low in copper, present significant challenges to traditional smelting processes, necessitating the need for more efficient and eco-friendly technologies. This project aims to optimize the smelting process by reducing metal losses and improving recovery rates of valuable metals from these challenging raw materials.

The research and development in this area have focused on various innovative technologies, such as high-temperature processes for the direct reduction of copper slag, complex technologies for depleting slag during the smelting of copper sulfide raw materials, and flotation enrichment methods. These approaches are essential for extracting valuable metals from slag and minimizing environmental impacts. For instance, the processing of rich converter and poor waste slags through flotation enrichment has shown significant promise in industrial applications, effectively separating valuable metals and improving recovery rates.

The software solution developed in this project incorporates a comprehensive mathematical model to simulate the smelting process. It predicts the yields and material flows, allowing for optimization of the smelting operations. The software includes modules for ore input, smelting simulation, and results presentation, providing a user-friendly interface for analyzing the impact of various process parameters on smelting efficiency. By simulating different scenarios, the software helps identify potential improvements in the smelting process, enhancing the recovery of valuable metals and reducing waste.

The industrial relevance of this software is underscored by the ongoing development of large copper deposits, such as the Boshchekul and Aktogay deposits in Kazakhstan, which contain high-sulfur, low-copper ores. The ability to accurately simulate the smelting process and optimize the chemical composition of alloys is crucial for these operations, as it allows for better management of resources and adherence to environmental regulations. The software was tested on data collected from the Balkhash copper smelter factory. For more trials, further data was obtained by changing the values to gather experimental trial. The software correctly reflects the real data when simulated. This shows the practicality and accuracy of the system developed.

In conclusion, the software developed provides a valuable tool for the copper smelting industry, enabling more efficient processing of high-sulfur, copper-poor concentrates. By leveraging advanced simulation techniques, it addresses the dual challenges of improving metal recovery and reducing environmental impact, thus supporting the industry's transition towards more sustainable practices.

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РАЗРАБОТКА КОМПЛЕКСНОГО ПРОГРАММНОГО РЕШЕНИЯ ДЛЯ ПЕРЕРАБОТКИ ВЫСОКОСЕРНИСТЫХ, МАЛОМЕДНЫХ КОНЦЕНТРАТОВ В МЕДЕПЛАВИЛЬНОЙ ПРОМЫШЛЕННОСТИ

Истощение богатых медных руд и увеличение доли бедных руд с высоким содержанием серы создают значительные проблемы для медеплавильной промышленности. Традиционные плавильные процессы сталкиваются с трудностями поддержания экономической эффективности и соблюдения экологических норм при переработке таких сложных руд. В данной работе описывается разработка комплексного программного решения, предназначенного для моделирования процесса плавки высокосернистых, маломедных концентратов. Программное обеспечение использует подробную математическую модель для прогнозирования выхода и состава продуктов, включая ценные металлы, в процессе плавки. Оно интегрирует несколько модулей, таких как ввод данных о руде, симуляция плавки и представление результатов, предоставляя удобную платформу для оптимизации плавильных операций. В модель включены такие ключевые параметры, как состав руды, температура плавки и добавление флюса, что позволяет точно прогнозировать выход штейна и шлака. Анализ этих результатов помогает *оптимизировать извлечение металлов и сократить потери, что в конечном итоге повышает эффективность и устойчивость медеплавильного производства. Этот инструмент особенно актуален для крупных месторождений сульфидных медных руд, таких как в Казахстане, которые имеют высокое содержание серы и низкий уровень меди. Способность программного обеспечения моделировать различные сценарии обработки предоставляет ценные сведения для промышленного применения, поддерживая разработку более эффективных и экологически чистых технологий плавки. Комплексное программное решение не только решает технические проблемы переработки высокосернистых, маломедных руд, но и способствует усилиям отрасли по снижению экологического воздействия и улучшению управления ресурсами. Это инновационное решение представляет собой значительный шаг вперед в оптимизации медеплавильных операций, способствуя устойчивости и эффективности в условиях ухудшения качества руды.*

Ключевые слова: *медеплавка, высокосернистые руды, симуляция плавки, извлечение металлов, оптимизация.*

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КҮКІРТІ ЖОҒАРЫ, МЫСЫ АЗ КОНЦЕНТРАТТАРДЫ ӨҢДЕУГЕ АРНАЛҒАН КЕШЕНДІ БАҒДАРЛАМАЛЫҚ ШЕШІМДІ ДАМЫТУ

Жоғары сапалы мыс кендерінің азаюы және күкірт мөлшері жоғары, мыс мөлшері аз концентраттардың үлесінің артуы мыс қорыту өнеркәсібіне елеулі қиындықтар тудырады. Дәстүрлі қорыту процестері мұндай күрделі кендерді өңдеуде экономикалық тиімділікті сақтап қалуға және экологиялық нормаларды сақтауға қиындық туғызады. Бұл жұмыста күкірт мөлшері жоғары, мыс мөлшері аз концентраттарды қорыту процесін модельдеуге арналған кешенді бағдарламалық шешімді әзірлеу сипатталады. Бағдарламалық қамтамасыз ету қорыту процесінде алынған өнімдердің, соның ішінде құнды металдардың шығынын және құрамын болжауға арналған егжей-тегжейлі математикалық үлгіні пайдаланады. Бұл бағдарлама бірнеше модульдерді біріктіреді: кенді енгізу, қорыту симуляциясы және нәтижелерді көрсету, қорыту операцияларын оңтайландыру үшін ыңғайлы платформа ұсынады. Модельге кеннің құрамы, қорыту температурасы және флюс қосуды қоса алғанда маңызды параметрлер енгізілген, бұл штейн мен шлактың шығуын дәл болжауға мүмкіндік береді. Осы нәтижелерді талдау металдарды алуды оңтайландыруға және шығындарды азайтуға көмектеседі, нәтижесінде мыс өндірудің тиімділігі мен тұрақтылығы артады. Бұл құрал Қазақстандағы сияқты күкірт мөлшері жоғары, мыс деңгейі төмен үлкен сульфидті мыс кен орындары үшін әсіресе өзекті. Бағдарламалық қамтамасыз етудің әртүрлі өңдеу сценарийлерін модельдеу мүмкіндігі өнеркәсіптік қолдану үшін құнды түсініктер береді және қорыту технологияларын неғұрлым тиімді және экологиялық таза етуге қолдау көрсетеді. Кешенді бағдарламалық шешім күкірт мөлшері жоғары, мысы аз рудаларды өңдеудің техникалық мәселелерін шешіп қана қоймай, саланың экологиялық әсерді азайту және ресурстарды басқаруды жақсарту жөніндегі күш-жігеріне де ықпал етеді. Бұл инновация мыс қорыту операцияларын оңтайландырудағы маңызды қадам болып табылады, кен сапасының төмендеуіне қарамастан, тұрақтылық пен тиімділікті арттыруға ықпал етеді.

Түйін сөздер: *мыс қорыту; күкірті жоғары рудалар; қорыту симуляциясы; металл алу; оңтайландыру.*

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