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«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

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ANALYSIS OF MODERN METHODS FOR CONTROL AND MANAGEMENT OF THE FLOTATION PROCESS

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Abstract. Froth flotation remains one of the primary methods for mineral resource beneficiation. Despite its widespread use, the process's overall efficiency depends heavily on accurate and timely control of its parameters, highlighting the need for improved automation technologies. Applied methods: This paper reviews current approaches to flotation process automation, focusing on smart technologies, real-time sensors, and predictive control systems. Particular attention is given to methods for pulp level regulation, airflow adjustment, reagent dosing, and pH monitoring. Additionally, the implementation of machine vision systems is considered as a complementary tool for flotation diagnostics and control. Main hypotheses and conclusions: The analysis of existing research underscores the

limitations of traditional control strategies and supports the shift toward hybrid, adaptive, and model-free techniques. These emerging approaches provide greater flexibility and responsiveness to process fluctuations. The integration of advanced sensor technologies, visual data processing, and predictive modeling can notably enhance the stability of flotation operations and improve mineral recovery efficiency. Practical significance: The findings of this work offer a scientific foundation for developing innovative automation solutions tailored to flotation processes. These solutions are aimed at optimizing operational performance, reducing manual intervention, and lowering energy and reagent consumption. As such, the adoption of intelligent control systems presents a promising path toward more sustainable and cost-effective mineral processing in modern industry.

Key words: flotation, process control, flotation automation, intelligent control, flotation optimization

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ФЛОТАЦИЯ ПРОЦЕСІН БАҚЫЛАУДЫҢ ЖӘНЕ БАСҚАРУДЫҢ ЗАМАНАУИ ӘДІСТЕРІН ТАЛДАУ

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Аннотация. Көбік флотациясы минералды ресурстарды байытудың негізгі әдістерінің бірі болып қала береді. Кең таралғанына қарамастан, бұл процестің жалпы тиімділігі көбінесе оның параметрлерін басқарудың дәлдігі мен уақтылығына байланысты, бұл автоматтандыру технологияларын

жетілдіру қажеттілігін көрсетеді. Қолданылатын әдістер: мақалада ақылды технологияларға, нақты уақыттағы сенсорларға және болжамды басқару жүйелеріне баса назар аудара отырып, флотация процесін автоматтандырудың заманауи тәсілдері қарастырылады. Целлюлоза деңгейін реттеу, ауа беру, реагенттерді мөлшерлеу және pH мониторингі әдістеріне ерекше назар аударылады. Сондай-ақ, флотация процесін диагностикалау мен басқарудың қосымша құралы ретінде машиналық көру жүйелерін енгізу қарастырылады. Негізгі гипотезалар мен қорытындылар: қолданыстағы зерттеулерді талдау дәстүрлі реттеу стратегияларының шектеулерін анықтайды және гибридті, бейімделгіш және модельсіз басқару әдістеріне көшу қажеттілігін растайды. Бұл жаңа тәсілдер жоғары икемділік пен процесс параметрлерінің ауытқуына төзімділікті қамтамасыз етеді. Жетілдірілген сенсорлық технологиялардың, визуалды аналитиканың және болжамды модельдеудің интеграциясы флотациялық операциялардың тұрақтылығын және минералды экстракцияның тиімділігін едәуір арттыра алады. Практикалық маңыздылығы: алынған нәтижелер флотацияны автоматтандыру саласындағы инновациялық шешімдерді әзірлеу үшін ғылыми негіз жасайды. Бұл шешімдер өндіріс тиімділігін арттыруға, қолмен араласу қажеттілігін азайтуға, сондай-ақ энергия шығыны мен реагенттердің шығынын азайтуға бағытталған. Зерттеу перспективалары: осы саладағы одан әрі ғылыми әзірлемелер өзін-өзі түзету алгоритмдерін жетілдіруге және модельдерді онлайн режимінде оқытуға бағытталуы мүмкін. Мультисенсорлық деректерді интерпретациялау және жүйелердің әртүрлі өңдеу жағдайларына бейімделуін арттыру саласындағы зерттеулер ерекше қызығушылық тудырады. Мұның бәрі минералды шикізатты байытудың интеллектуалды, автономды және тиімді технологияларын қалыптастыруға ықпал етеді.

Түйін сөздер: флотация, процесті басқару, флотацияны автоматтандыру, интеллектуалды басқару, флотацияны оңтайландыру

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АНАЛИЗ СОВРЕМЕННЫХ МЕТОДОВ ПО КОНТРОЛЮ И УПРАВЛЕНИЮ ПРОЦЕССОМ ФЛОТАЦИИ

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Аннотация. Пенная флотация остаётся одним из основных методов обогащения минеральных ресурсов. Несмотря на широкое распространение, общая эффективность данного процесса в значительной степени зависит от точности и своевременности управления его параметрами, что подчёркивает необходимость совершенствования технологий автоматизации. Применяемые методы. В статье рассматриваются современные подходы к автоматизации процесса флотации с акцентом на умные технологии, сенсоры реального времени и системы предиктивного управления. Особое внимание уделено методам регулирования уровня пульпы, подачи воздуха, дозирования реагентов и мониторинга pH. Также рассматривается внедрение систем машинного зрения как дополнительного инструмента диагностики и управления флотационным процессом. Основные гипотезы и выводы. Анализ существующих исследований выявляет ограничения традиционных стратегий регулирования и подтверждает необходимость перехода к гибридным, адаптивным и безмодельным методам управления. Эти новые подходы обеспечивают более высокую гибкость и устойчивость к колебаниям параметров процесса. Интеграция передовых сенсорных технологий, визуальной аналитики и предиктивного моделирования способна значительно повысить стабильность флотационных операций и эффективность извлечения минералов. Практическая значимость. Полученные результаты создают научную основу для разработки инновационных решений в области автоматизации флотации. Эти решения направлены на повышение производственной эффективности, снижение необходимости ручного вмешательства, а также сокращение энергозатрат и расхода реагентов. Перспективы исследований. Дальнейшие научные разработки в данной области могут быть направлены на совершенствование алгоритмов самокоррекции и обучение моделей в режиме онлайн. Особый интерес представляют исследования в области интерпретации мультисенсорных данных и повышения адаптивности систем к различным условиям переработки. Всё это будет способствовать формированию более интеллектуальных, автономных и эффективных технологий обогащения минерального сырья.

Ключевые слова: флотация, управление процессом, автоматизация флотации, интеллектуальное управление, оптимизация флотации

Introduction

Froth flotation is one of the most widely used beneficiation methods in the mining industry. However, many years of experience in research and process development show that flotation is still not fully understood and is relatively imperfect. Thus, significant economic benefits can be achieved by optimizing a number of current processes (McKee, 1991). Based on this, the flotation process control strategy is formed as a multidimensional and interrelated hierarchy (Jovanovic, et al., 2015).

Effective process management begins with the right tools - these are the devices that form the basis of the entire process management. Also, effective selection of devices is possible only with a deep knowledge of their operation and the application of the required device in the context of a given process.

Flotation control is focused on maintaining key parameters and setpoints. Key parameters include pulp level, air flow, and reagent injection rate. This is typically achieved using standard PID control (Albertus, et al., 2025). Similarly, standard control was used for individual cells, but modern control strategies are now often applied to entire flotation cells.

To optimize the flotation process, the problems of stabilizing the control of process parameters in the event of deviations caused by changes in the input raw materials, as well as maintaining the established values of key performance indicators, which include: the content of the target component and its degree of extraction, are studied. Considering economic parameters such as reagent price and product market value, flotation optimization is a key tool to improve performance and reduce costs. The main objective of these methods is to increase the overall economic profit, which is usually achieved by increasing recovery and improving concentrate quality. Thus, the complex elements of the flotation process are controlled by selecting the correct setpoints, which ensures stability and predictability of the process regime. These conditions serve as the foundation for successful parameter adjustment and stable production results.

Materials and methods

Flotation is a separation process involving three phases simultaneously: solid, liquid and gaseous, which are represented by fine particles in multi-component ore smaller than 0.1 mm (usually smaller than 0.074 mm), water and air bubbles. The flotation results are significantly affected by the characteristics of the interacting phases and the physicochemical reactions occurring at the boundaries of their separation. The key factor is the different ability of mineral particles to absorb water. The natural wettability of minerals can be both hydrophobic and hydrophilic. However, flotation capacity can be adjusted by introducing flotation reagents into the pulp. These reagents are chemical compounds that specifically affect the pulp and minerals. To carry out flotation, an aerated pulp is used, to which heteropolar substances are added, stabilizing air bubbles and promoting the formation of stable foam that retains minerals. All the above stages are carried out in flotation cells (main and cleaning) according to a developed scheme, which is schematically presented in the section surrounded by a dotted line in Figure 1 (Gaete-Garretón, 2015).

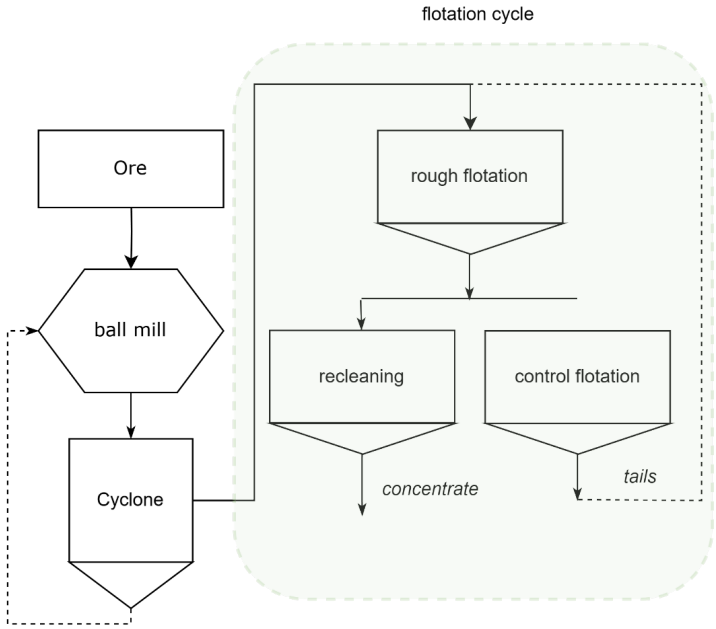

Figure 1 - Schematic representation of the flotation process

The complexity of the flotation process used in beneficiation is highlighted by assessments that highlight the need for accurate and reliable measurement of a number of key parameters (Azizi, et al., 2020). In addition, efforts to control the interactions between parameters become even more challenging. For example, an increase in air flow rate can cause an increase in bubble size, which in turn will affect their rise rate, adhesion rate, gas retention time, froth depth, etc. (Hell, et al., 2024).

In addition, any change in one of the chambers (e.g., in the cleaning circuit) affects the pulp composition and the flow rate of each stream leaving this chamber. This change also affects all subsequent stages of the process and even earlier stages such as re-flotation. For example, when processing sulphide copper and zinc ores, an increase in the pulp level in the finishing chamber causes the extraction of not only a greater amount of target minerals into concentrate, but also gangue along with water. An increased material content in the concentrate during re-cleaning leads to an increase in the pulp flow rate entering the rougher flotation stage, which reduces the residence time in the flotation cells. These changes occurring at the cleaning stage affect the final results: the extraction of valuable components increases, but its content in the final concentrate decreases (Meng, et al., 2016).

It is important to consider that the interaction of changes in more than one variable over a short period of time can result in long-term disruption to the flotation system. Therefore, Table 1 summarizes the variables and their complex, nonlinear relationships.

Table 1. Key variables of the flotation process

Category	Process variables	Control factors
Physical	Pulp density	Regulation of solid and liquid feed, pulp dilution control
	Pulp solids content	Regulation of solid and liquid feed, pulp dilution control
	Pulp flow rate (retention time)	Regulation of pulp feed rate, change of flotation cell volume
	Pulp level in flotation cells	Regulation of pulp release from the cell, control of liquid supply
	Air consumption in flotation cells	Regulating air supply by compressor, setting up air distributors
	Foam properties (flow rate, bubble size, stability)	Regulation of foaming agent supply, pulp level control, air flow control
	Particle size and shape, degree of mineral disclosure	Preliminary processing of ore (crushing, grinding), regulation of the grinding process
	Consumption of washing water (in column flotation machines)	Regulation of water supply to the column, control of the height of the foam layer
Chemicals	pH of pulp	Adding pH regulators (acid or alkali), water quality control
	Oxidation-reduction potential (Eh) of pulp	Addition of oxidizing or reducing agents, control of electrochemical processes
	Electrical conductivity of pulp	Control of ionic composition of water, addition of reagents
	Type and dosage of flotation reagents (frothing agents, collectors, depressors, activators)	Automated reagent dosing systems, manual dosage adjustment, selection of the optimal reagent type depending on the ore composition and the required results

To achieve effective control of the flotation process, it is not always necessary to measure and control every variable simultaneously. However, the impact of each variable on the flotation process must be considered, since even small deviations can have a cumulative effect.

Results. In this context, the flotation plant configuration is of particular importance, as it directly affects the control capabilities and accuracy. In particular, the presence of recirculation flows can significantly complicate the control of, for example, the pulp level, especially if uncontrolled accumulation or release of material occurs (Michaux, et al., 2020). In addition, different sections of the plant require the use of different control strategies. Thus, at the roughing and scavenging stages, where the priority is to maximize the recovery of valuable components, modes with a low froth depth and high air flow are usually used (Zhao, et al., 2025). At the same time, at the finishing stages, the purpose of which is to improve the quality of the concentrate, modes with a greater froth depth and reduced air flow are preferable.

However, even under optimal operating conditions, process stability largely depends on the ability of the system to respond in a timely manner to external

and internal disturbances. Therefore, to effectively control flotation, it is important to understand the characteristics, frequency, and intensity of input disturbances. Provided that the control systems in the grinding circuit operate reliably (Mathe, et al., 2021), changes in feed rate, pulp density, and particle size should be small. At the same time, the flotation circuit must compensate for changes in ore mineralogy and floatability. Data on input disturbances, current operating conditions and product quality are critical for operational and strategic decision making. However, despite the availability of instrumentation to measure important parameters such as ore composition, flow rate and less specific ore properties (e.g. pulp level, density, pH), important properties such as recovery rate, surface chemistry, bubble size distribution, bubble loading remain difficult to measure and directly impact recovery efficiency (Heng, et al., 2024).

In response to these challenges, modern flotation control methods increasingly use intelligent technologies. Current control systems for mechanical flotation cells are improved by the introduction of intelligent model-predictive control algorithms that complement the classic PID controllers that remain the basis for maintaining key parameters at the level of individual sections and devices. To apply this method in practice, a reliable hardware base is required: air flow sensors, ultrasonic level meters and digitally controlled actuators that ensure long-term stability and flexibility of the entire flotation complex (Jovanović, et al., 2015). The development of measurement technologies is of particular importance as flotation cells grow. Figure 2 shows a pH monitoring system implemented in a flotation cell (Barry, et al., 2016).

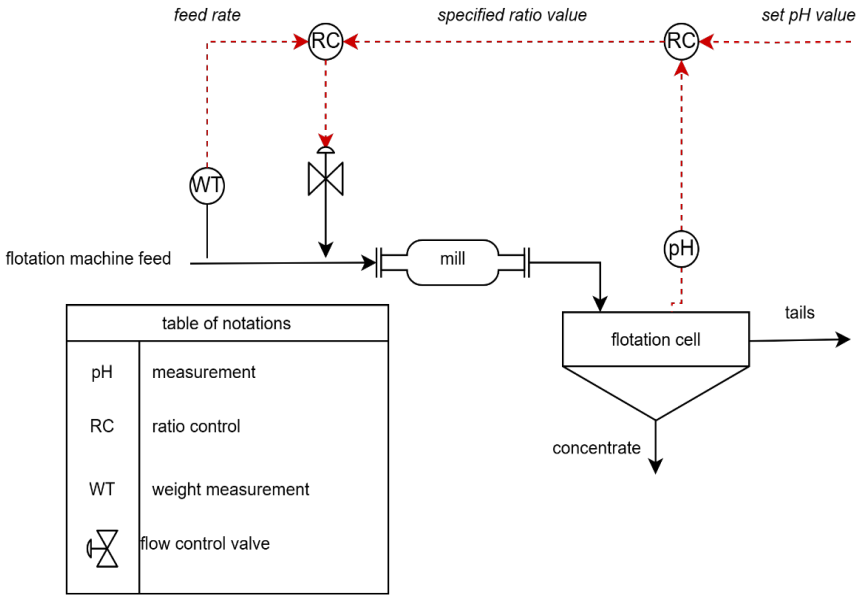

Figure 2. pH control in the flotation circuit

Modern approaches to increasing the volume of flotation cells combine kinetic models and empirical methods, however, froth transport in large cells remains an important unsolved problem that requires a combination of design solutions and froth dynamics models (Mesa, et al., 2019). Flotation cell control focuses on maintaining a constant pulp level and maximizing the recovery of valuable minerals in the concentrate, while separating gangue into tailings, which allows for effective control of key parameters and optimization of mineral separation (le Roux, et al., 2019).

At the same time, the focus is on air flow control and foam dynamics management. A multi-parameter sensor with a Double-Path algorithm has been studied, which provides accurate monitoring of motion in real time and can be used to analyze hydrodynamic processes in industrial flotation cells (Mazzoli, et al., 2025). It has been proven that reducing the air feed rate contributes to more stable foam formation and improves the mechanism of retention of large particles in the pulp, which allows to increase the efficiency of copper beneficiation in flotation machines (Gacitúa, et al., 2023). Modern submersible sensors for industrial flotation cells provide accurate and continuous measurements of key pulp parameters, such as gas content and density, which significantly increases the efficiency of process control and optimization (Maldonado, et al., 2024).

Modern approaches to pulp composition analysis also contribute to optimized control. A new generation of in-line sensors for industrial flotation devices offers accurate and continuous measurements of key pulp properties such as gas content and density, significantly improving process control and optimization capabilities. Thus, real-time elemental analysis using in-line XRF analyzers like FLORIDA enables rapid and cost-effective copper content monitoring. Automation of reagent dosing is especially important in conditions of unstable feedstock. Given the continuous changes in ore properties such as particle size, flow rate, and concentration, the dosing system must be adjusted in real time to stabilize the process and improve flotation efficiency (Kejonen, et al., 2018).

Thus, automation of reagent management focuses on creating stable conditions for flotation and maximizing recovery, while reducing human influence and system response to process disturbances. Monitoring electrochemical parameters such as Eh, pH, and conductivity remains an equally important element in the automatic control system. Measuring electrochemical potential (Eh) and pH is one of the key technologies that helps to better understand and control the oxidation and reduction processes that affect the recovery of metals such as copper and lead in the flotation circuit (Gaosong yi, 2023). Case studies have shown that optimizing electrochemical potential improves flotation efficiency, but different types of electrodes such as platinum, mineral, and ion-selective provide diverse information, requiring an integrated approach to real-time analysis and reagent dosing (Heng, et al., 2023). Combining predictive models, such as slurry pH correction, can take into account the effects of ore composition and dynamic processes in bauxite flotation, ensuring

accurate and timely monitoring. The use of autoregressive algorithms and expert correction ensures the stability of the control system and forms the basis for the implementation of predictive systems in flotation plants (Lu, et al., 2023).

Discussion

The conducted analysis of modern methods for control and management of the flotation process, focuses on the main aspects of these parameters. The relevance of the topic of this study in the study of this area by students and scientists will help and expand their perception from a new point of view.

Conclusions

Modern approaches to flotation control include the integration of advanced technologies such as multi-parameter and submersible sensors, automated reagent dosing systems, electrochemical parameter monitoring systems and real-time elemental analysis. This allows for more efficient process control, adaptation to changes in raw materials and optimum recovery of valuable components, leading to increased productivity and reduced costs in the mining industry. In the future, we can expect further development of intelligent control systems capable of self-learning and adapting to even more complex conditions.

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