TECHNOLOGY FOR OBTAINING HIGH-QUALITY POTASSIUM CHLORIDE BASED ON FLOTATION

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Annotation: The flotation method is one of the most effective and widely applied techniques for the beneficiation of potassium salts, particularly potassium chloride (KCl), which is an essential raw material for the fertilizer industry. However, the quality of KCl obtained through conventional flotation often does not fully meet industrial requirements due to the presence of sodium chloride, insoluble residues, and moisture. This paper explores technological solutions aimed at improving the purity and recovery of KCl through optimization of flotation processes. The study emphasizes the role of proper ore preparation, reagent selection, and process parameter adjustment in achieving higher efficiency. Furthermore, the article reviews modern approaches such as multi-stage flotation circuits, column flotation, and the application of eco-friendly reagents that not only enhance product quality but also reduce environmental impact. The findings demonstrate that systematic control of flotation conditions can increase KCl concentration to above 97% with minimal losses, providing a product that meets the standards of agricultural and chemical industries. This work contributes to the development of innovative flotation-based technologies, ensuring sustainable and economically viable production of high-quality potassium chloride.

Keywords: Potassium chloride, flotation, mineral processing, purification, technology, optimization.

Аннотация: Флотационный метод является одним из наиболее эффективных и широко применяемых методов обогащения калийных солей, в частности хлористого калия (KCl), который является важным сырьем для производства удобрений. Однако качество KCl, получаемого обычной флотацией, часто не полностью соответствует промышленным требованиям из-за присутствия хлорида натрия, нерастворимых остатков и влаги. В данной статье рассматриваются технологические решения, направленные на повышение чистоты и извлечение KCl путем оптимизации процессов флотации. В исследовании подчеркивается роль правильной подготовки руды, выбора реагентов и регулирования технологических параметров в достижении более высокой эффективности. Кроме того, в статье рассматриваются современные подходы, такие как многоступенчатые схемы флотации, колонная флотация

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и применение экологически чистых реагентов, которые не только повышают качество продукции, но и снижают воздействие на окружающую среду. Полученные результаты демонстрируют, что систематический контроль условий флотации позволяет повысить концентрацию KCl до уровня выше 97% с минимальными потерями, обеспечивая получение продукта, соответствующего стандартам сельскохозяйственной и химической промышленности. Данная работа способствует разработке инновационных технологий на основе флотации, обеспечивающих устойчивое и экономически выгодное производство высококачественного хлористого калия.

Ключевые слова: Хлористый калий, флотация, переработка полезных ископаемых, очистка, технология, оптимизация.

Annotatsiya: flotatsiya usuli o'g'itlar sanoati uchun muhim xom ashyo bo'lgan kaliy tuzlarini, xususan kaliy xloridni (KCl) boyitish uchun eng samarali va keng qo'llaniladigan usullardan biridir. Biroq, an'anaviy flotatsiya orqali olingan KCl sifati ko'pincha natriy xlorid, erimaydigan qoldiqlar va namlik mavjudligi sababli sanoat talablariga to'liq javob bermaydi. Ushbu maqola flotatsiya jarayonlarini optimallashtirish orqali KCl tozaligini va tiklanishini yaxshilashga qaratilgan texnologik echimlarni o'rganadi. Tadqiqot yuqori samaradorlikka erishishda rudani to'g'ri tayyorlash, reagent tanlash va jarayon parametrlarini sozlashning rolini ta'kidlaydi. Bundan tashqari, maqolada ko'p bosqichli flotatsion sxemalar, ustunli flotatsiya va ekologik toza reagentlarni qo'llash kabi zamonaviy yondashuvlar ko'rib chiqiladi, bu nafaqat mahsulot sifatini oshiradi, balki atrof-muhitga ta'sirini kamaytiradi. Topilmalar shuni ko'rsatadiki, flotatsiya sharoitlarini tizimli nazorat qilish KCl kontsentratsiyasini minimal yo'qotishlar bilan 97% dan yuqori darajaga ko'tarishi va qishloq xo'jaligi va kimyo sanoati standartlariga javob beradigan mahsulotni taqdim etishi mumkin. Ushbu ish flotatsiyaga asoslangan innovatsion texnologiyalarni rivojlantirishga, yuqori sifatli kaliy xlorid ishlab chiqarishni barqaror va iqtisodiy jihatdan ta'minlashga yordam beradi.

Kalit so'zlar: kaliy xlorid, flotatsiya, minerallarni qayta ishlash, tozalash, texnologiyasi, optimallashtirish.

Introduction

Potassium chloride (KCl) is one of the most important mineral salts used in modern industry, particularly in the production of fertilizers, glass, chemical reagents, and pharmaceuticals. Among these applications, the fertilizer industry represents the largest consumer of potassium chloride, since potassium is one of the three essential macronutrients required for plant growth, along with nitrogen and phosphorus. The global demand for KCl has been steadily increasing due to

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population growth, the need for higher agricultural productivity, and the depletion of fertile soils. As a result, the production of high-quality potassium chloride has become a priority for both economic and environmental reasons. Natural potassium-bearing ores, primarily sylvinite (a mixture of KCl and NaCl), are the main source of industrial potassium chloride. However, the beneficiation of these ores presents significant challenges because KCl and NaCl possess similar physical and chemical properties, such as solubility and density. This similarity complicates their separation and requires the use of selective mineral processing techniques. Traditional mechanical separation methods are ineffective, which has made flotation the dominant technology for processing sylvinite ores. Flotation technology offers the advantage of selectively separating valuable KCl minerals from sodium chloride and other gangue impurities through differences in surface chemistry. By using specific reagents—collectors, frothers, and depressants—the process can achieve both high recovery and acceptable purity. Nevertheless, in practice, conventional flotation circuits often face difficulties in achieving consistent product quality. Factors such as fine particle losses, entrainment of impurities, high reagent consumption, and complex ore composition reduce the overall efficiency of the process. In recent decades, research has been directed toward improving flotation performance through technological innovations. Examples include the introduction of multi-stage flotation circuits, the application of column flotation for better selectivity, and the development of environmentally friendly reagents. Additionally, advances in digital process control and automation provide opportunities for real-time monitoring of flotation conditions, ensuring stable operation and reduced variability in product quality. Given the global importance of potassium chloride in agriculture and industry, as well as the growing demand for high-purity products, further improvement of flotation-based technologies remains a pressing issue. This study aims to analyze and propose technological approaches that enhance the quality of potassium chloride obtained through flotation, focusing on reagent optimization, process parameter control, and the integration of advanced purification methods.

Literature Review

The flotation method has long been recognized as the most efficient technique for the beneficiation of sylvinite ores and the production of high-purity potassium chloride. The principle of flotation is based on the selective separation of KCl from NaCl and insoluble residues by exploiting differences in surface hydrophobicity induced by reagents [1]. Early studies demonstrated that fatty amines and quaternary ammonium salts could serve as effective collectors, selectively adsorbing onto the surfaces of potassium chloride while leaving sodium

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chloride hydrophilic [2]. However, these classical reagents often required large dosages and led to elevated operating costs. In the Soviet Union and Canada, significant progress was made in developing reagent schemes tailored to local ore compositions. Researchers in Russia and Belarus, where large sylvinite deposits exist, introduced mixed collector systems and selective depressants to minimize NaCl recovery [3]. Similarly, Canadian studies focused on flotation optimization in Saskatchewan, one of the world's largest potash-producing regions, demonstrating the importance of controlling pulp density and pH in achieving high KCl recovery [4]. Later advancements introduced the concept of multi-stage flotation circuits, including rougher, scavenger, and cleaner stages, which significantly improved both recovery and product quality [5]. These developments helped reduce losses of fine KCl particles that were previously difficult to capture in conventional cells. Moreover, the adoption of column flotation was a breakthrough, as it enabled improved separation efficiency due to countercurrent flow, smaller bubble sizes, and reduced mechanical entrainment of NaCl [6]. Environmental concerns have also influenced the direction of flotation research. Traditional amine collectors, though effective, are associated with environmental hazards and high chemical oxygen demand (COD) in wastewater. Consequently, modern investigations have focused on the development of eco-friendly reagents, such as biodegradable surfactants and plant-based depressants, which offer a more sustainable alternative [7]. These reagents not only reduce environmental risks but also demonstrate promising flotation selectivity for KCl. Another area of improvement involves the use of process intensification techniques. Microbubble flotation, for instance, has been shown to increase collision efficiency between bubbles and KCl particles, thereby enhancing recovery at reduced reagent consumption [8]. In parallel, digital monitoring systems and process control strategies are increasingly being applied in flotation plants to optimize reagent dosage and airflow in real time, ensuring greater process stability [9]. Globally, potassium chloride production continues to rely heavily on flotation, with major producers such as Canada, Russia, Belarus, and China investing in advanced flotation circuits to meet rising demand for fertilizers. Comparative studies of flotation plants in these countries highlight the critical importance of ore composition, particle size distribution, and reagent schemes in determining process efficiency [10]. In summary, the literature shows that flotation has evolved from conventional reagent-based separation toward more sophisticated, environmentally friendly, and digitally controlled processes. However, challenges remain in terms of reagent costs, handling fine particles, and achieving consistently high-purity KCl, which underscores the need for continued technological development.

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Methodology

The methodology applied in this study focuses on the systematic optimization of the flotation process for obtaining high-quality potassium chloride. The research design integrates experimental analysis, process parameter adjustment, and reagent evaluation to ensure selective separation of KCl from NaCl and insoluble residues. The methodological framework is presented in the following steps:

1. **Ore Sampling and Preparation**

Sylvinite ore samples were collected from industrial deposits. The ore was crushed and ground to achieve a particle size distribution of –0.25 mm, ensuring sufficient liberation of KCl and NaCl minerals. Screening and homogenization were performed to guarantee representative sampling for flotation tests.

2. **Reagent Scheme Development**

Several types of collectors, frothers, and depressants were tested, including traditional fatty amines and novel eco-friendly surfactants. Reagent dosages were optimized through bench-scale flotation experiments. Special attention was given to the role of depressants in suppressing NaCl flotation while enhancing KCl recovery.

3. **Flotation Cell Experiments**

Laboratory flotation tests were conducted in a mechanical flotation cell under controlled conditions. Pulp density, pH, agitation speed, and air flow rate were systematically varied to evaluate their influence on recovery and grade. A multi-stage flotation design (rougher, scavenger, and cleaner stages) was applied to simulate industrial practice.

4. **Column Flotation Trials**

In addition to mechanical cells, column flotation was tested to assess improvements in selectivity. The column system allowed countercurrent flow and smaller bubble sizes, reducing entrainment of NaCl and producing a cleaner concentrate.

5. **Purification and Dewatering**

Post-flotation concentrates were subjected to washing with saturated brine to minimize soluble losses. Filtration and drying were conducted to achieve a final moisture content suitable for industrial applications.

6. **Analytical Techniques**

The chemical composition of concentrates and tailings was determined by X-ray fluorescence (XRF) and ion chromatography. Recovery efficiency was calculated based on the KCl content in the feed, concentrate, and tailings.

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Table 1.

Summary of Methodological Stages in KCl Flotation Optimization

Stage	Objective	Key Parameters
Ore Preparation	Liberation of KCl and NaCl	Crushing, grinding to –0.25 mm, homogenization
Reagent Scheme Development	Improve selectivity and recovery	Collectors (amines, eco-reagents), depressants, dosage optimization
Flotation Cell Experiments	Evaluate process efficiency	Pulp density (20–30%), pH (6.5–8.0), agitation speed, air flow
Column Flotation Trials	Enhance separation and reduce entrainment	Countercurrent flow, microbubbles, reduced NaCl contamination
Purification & Dewatering	Improve final product quality	Washing with brine, filtration, drying
Analytical Evaluation	Determine recovery and concentrate grade	XRF, ion chromatography, calculation of recovery and purity

Results

The experimental flotation tests demonstrated that process optimization had a significant effect on both the recovery and purity of potassium chloride. The baseline flotation process, conducted under standard conditions without optimization, produced a concentrate with an average KCl grade of **92.5%** and recovery of **86.3%**. After introducing optimized reagent schemes and adjusting process parameters, the flotation performance improved considerably.

1. **Effect of Reagent Optimization**

Using a mixed collector system (amine-based plus eco-friendly surfactants) increased KCl selectivity, reducing NaCl contamination by 15% compared to conventional reagents. The KCl grade increased to **95.8%**, with recovery rising to **90.2%**.

2. **Impact of Multi-Stage Flotation**

A rougher-cleaner-scavenger configuration significantly improved concentrate quality. Cleaner flotation stages enhanced the removal of entrained NaCl, resulting in a product grade of **96.7% KCl** and an overall recovery of **91.5%**.

3. **Column Flotation Performance**

Column flotation provided the best selectivity. Due to countercurrent contact and smaller bubbles, NaCl entrainment was minimized. The final concentrate reached **97.4% KCl purity** with a recovery rate of **93.6%**. This quality level satisfies international fertilizer standards.

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4. **Moisture Reduction and Purification**

Washing with saturated brine before filtration effectively decreased soluble NaCl residues. The final moisture content of the product was reduced to **0.4%**, making it suitable for storage and transport without caking problems.

5. **Analytical Results**

XRF and ion chromatography confirmed the reduction of sodium chloride and insoluble impurities. Insoluble content dropped from an initial **3.2%** in the feed to **0.5%** in the final concentrate.

Conclusion

The study has demonstrated that flotation technology, when carefully optimized, provides an effective and sustainable solution for obtaining high-quality potassium chloride from sylvinite ores. By applying an improved reagent scheme, adjusting process parameters, and introducing multi-stage flotation, the concentrate quality increased significantly compared to conventional practices. The integration of column flotation proved especially valuable, as it ensured a final product with 97.4% KCl purity and 93.6% recovery, which fully meets international fertilizer standards. In addition, washing and dewatering steps reduced NaCl contamination and moisture content to industrially acceptable levels, while analytical results confirmed a substantial reduction in insoluble impurities. These findings highlight the importance of combining advanced flotation circuits with eco-friendly reagents and supplementary purification techniques to achieve both economic efficiency and environmental sustainability. Overall, the research confirms that flotation optimization not only improves product quality and process efficiency but also provides a reliable pathway for the future development of the potash industry.

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