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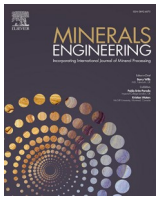

A review of fine particle flotation: mechanistic insights and advances

Mohammad Hossein Ghasemi Flavarjani [a], Arash Sobouti [a], Bahram Rezai [a,*], Ali Ahmadi [b]

[a] Department of Mining Engineering, Amirkabir University of Technology, Tehran 150754413, Iran
[b] Department of Mining Engineering, Isfahan University of Technology, Isfahan, Iran

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ABSTRACT

Fine particle flotation has emerged as a critical area in mineral processing due to increasing demand for resource recovery and the growing presence of ultrafine particles in ore deposits and tailings. These particles, typically smaller than 38 μm, pose significant challenges including low mass, high surface energy, high reagent consumption, and reduced bubble-particle collision efficiency. This review provides a comprehensive analysis of the mechanisms affecting the flotation of fine particles and explores various technical strategies developed to overcome these limitations. These include particle size enlargement through flocculation and agglomeration, bubble size reduction via micro- and nanobubbles, and advanced cell designs aimed at improving particle-bubble interaction. Emerging technologies such as dissolved air flotation, electroflotation, and pneumatic and column cells are also discussed. Furthermore, the article critically evaluates the applicability, limitations, and industrial scalability of these methods. Emphasis is placed on integrating environmentally friendly reagents and optimizing process efficiency to enhance sustainability in mineral processing. The review concludes by outlining future research needs, including the multivariate study of interacting flotation parameters and the development of industrial-scale solutions for fine particle recovery.

1. Introduction

The advancement of mining technologies and the growing global demand for mineral resources have led to the intensified exploitation of mineral deposits. This trend has contributed to a decline in high-grade ore reserves with simple mineralogical compositions (Fig. 1). As a result, the extraction of minerals is increasingly shifting toward low-grade ore bodies with complex mineralogies. These deposits often exhibit a low degree of liberation, necessitating additional comminution to achieve the required level of mineral separation.

Furthermore, during mining, extraction, transportation, and comminution, a substantial portion of mineral resources is converted into fine particles (FPs). According to standard references in mineral processing, FPs are typically defined as particles smaller than 38 μm, while ultra-fine particles are those under 13 μm (Ahmadi and Khodadadi Darban, 2013). The presence of FPs in processing circuits reduces separation efficiency and leads to increased operational costs. As a result, such particles are often removed using cyclones and discharged into tailings ponds.

However, the accumulation of FPs in tailings ponds has led to serious environmental concerns. In response, there is a growing interest in reutilizing mineral tailings containing both fine and coarse particles as secondary resources. For example, at the SarCheshmeh copper complex in Iran, approximately 25 % of copper losses occur in particles smaller than 23 μm (Fig. 2).

Recent advancements in comminution techniques have enabled the processing of complex ores that include valuable gangue minerals. Additionally, the reprocessing of mineral tailings containing FPs has become a viable and sustainable solution. Therefore, conducting focused research on FP processing offers significant economic and environmental benefits.

As illustrated by the flotation size–recovery curve in Fig. 3, flotation efficiency declines sharply for particles smaller than 38 μm. This highlights the practical importance of developing innovative flotation methods specifically designed for FPs (Cheng et al., 2023; El-bahi et al., 2024; Farrokhpay et al., 2021; Fornasiero and Filippov, 2017; Sajjad and Otsuki, 2022).

The reasons behind the low efficiency in particle flotation depend on various chemical and hydrodynamic factors (Fig. 4) (Tabosa et al., 2013). FPs, which have a significantly larger surface area compared to coarse particles, require excessive collectors. Additionally, these FPs tend to develop more surface coatings, likely due to their increased

* Corresponding author.
E-mail address: rezai@aut.ac.ir (B. Rezai).

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