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Foams stabilization by silica nanoparticle with cationic and anionic surfactants in column flotation: Effects of particle size

Nan Hu[a], Yanfei Li[b], Zhaoliang Wu[a,*], Ke Lu[a], Di Huang[a], Wei Liu[a,*]

[a] School of Chemical Engineering and Technology, Hebei University of Technology, No.8 Guangrong Road, Dingzi Gu, Hongqiao District, Tianjin 300130, China
[b] State Key Laboratory of Chemical Resource Engineering, Beijing University of Chemical Technology, Beijing 100029, China

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ABSTRACT

Foams have been widely used in flotation, but they stabilized solely by surfactants was unstable. Nanoparticles (NPs) can improve the performance of aqueous foams. It is interesting to evaluate and understand the effect of NPs on foam property in column flotation. In this paper, silica nanoparticles (SNPs) with three different sizes (20, 100 and 500 nm) were chosen as model NPs; the performance of foams stabilized by SNPs and two surfactant, cetyltrimethylammonium bromide (CTAB) and anionic sodium dodecylsulfate (SDS), were investigated experimentally. For CTAB/SNPs dispersion, although the foamability was lower, SNPs obviously improved static foam stability. Moreover, smaller SNP exhibited a more effective improvement for foam stability because of its low adhesion energy and high number concentration. For SDS/SNPs dispersion, even if SNPs were hydrophilic, the foam stability was still enhanced since these particles induced congestion in the node and slowed down drainage. Larger SNP had a greater ability to delay the liquid drainage and enhance the foam stability. Besides, CTAB/SNPs and SDS/SNPs foams also maintained their dynamic stability through weakening the foam drainage. These results provided theoretical supports for the usage of NPs in practical application such as flotation.

1. Introduction

As the importance and popularity of foams in industrial and engineering processes, such as food industry, flotation and enhanced oil recovery [1,2], the manipulation of foam stability and their fundamental research is becoming a hotspot. However, the high specific surface area and energy of foams make them unstable both thermodynamically and kinetically [2], which are detrimental to the practical operation. So it is urgent to develop a foam system with long-term stability.

Flotation is an important separation technology for the recovery and concentration of valuable minerals from ores [3]. Foams play a critical role in transporting particles into foam phase, thereby determining the separation efficiency and selectivity of flotation. Traditionally, surfactants are used to prepare and stabilize foams. Their molecules lie at the air–water interface to reduce the surface tension and prevent gaseous bubbles from coalescing [4]. Unfortunately, surfactants are unable to maintain foam stability for a long time in the presence of external disturbances (such as washwater), owing to their low adhesion energy at the interface [5]. On the other hand, with increasing foam height and residence time in a flotation column, the desorption of surfactants may easily occur and the film thinning becomes rapid as a result of liquid drainage [6]. Eventually, the carrying capacity of foams weakens, and then some particles or ions may be detached and lost from the foam.

With the advances in nanotechnology, nanoparticle (NP) has been emerged as an excellent candidate to stabilize aqueous foams and emulsions. Binks and Horozov [7] found that aqueous foams could be stabilized by silica NPs (SNPs) without the presence of surfactants. No foam was formed with the particles that were hydrophilic or highly hydrophobic. Furthermore, Cui et al. [8] used $CaCO_3$ NPs with anionic surfactants to generate foams in aqueous media. Arriaga et al. [9] investigated the foam property of aqueous dispersion containing mixture of SNPs and a short-chain amphiphile (*n*-amylamine). The both systems were able to produce exceptionally stable foams by controlling the NP hydrophobicity and the surfactant concentration, demonstrating the synergy between the NP and the surfactant. This remarkable stability is mainly attributed to the irreversible adsorption of NPs on the interface [9]. More importantly, the adsorbed NPs in the film between neighboring bubbles form solid-like surface layers, creating a steric barrier to coalescence and coarsening [10]. Therefore, NP-stabilized foams appear to be a promising method for satisfying the requirement of flotation.

* Corresponding authors.
E-mail addresses: zhaoliangwu_hebut@163.com (Z. Wu), liuw16018@hebut.edu.cn (W. Liu).

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Table 1
Properties of the SNPs used for the experiment.

Type of SNPs	Hydrodynamic diameter (nm)	Zeta potential (mV)	Contact angles (°)
20 nm SNP	34.6 ± 1.7	−29.9 ± 1.5	30.4 ± 1.5
100 nm SNP	137.2 ± 6.9	−33.8 ± 1.7	33.8 ± 1.7
500 nm SNP	602.7 ± 30.1	−36.5 ± 1.8	36.7 ± 1.8

The key to set up NP-stabilized foams in flotation is to have a clear understanding the effect of NPs on foam property. The degree of NPs hydrophobicity is generally considered the foundation of aqueous foam stability [10]. Most NPs are naturally hydrophilic and then contribute little to aqueous foam stability because their adsorption on the interface is limited or inadequate [11]. Even if NPs are hydrophilic, flotation process can recover them in foam phase by the entrainment, which is related directly to foam stability [5]. To the best of our knowledge, there are only a few literatures that evaluated the ability of hydrophilic NP to act as a foam stabilizer in flotation. This critical issue is unclear and remains open. Furthermore, more efforts are also required to elucidate the influence of NPs size on the foam stability, considering that their unique properties are originated from their small size. Some researchers concluded that the stability of foams and emulsions is proportional to NP size [12]. Nevertheless, the calculation by Binks and Lumsdon [13] showed that the detachment energy associated with the escape from the liquid film became small when the particle size was smaller than 100 nm, which adversely affected the foam stability in Pickering emulsion. Consequently, systematical experiments are needed to figure out the relationship between NPs size and foam stability.

In this study, SNPs were chosen as a model stabilizer in a column flotation, on account of their favorable attributes, including large surface energy, easy modification, good chemical stability and low cost [11]. Meanwhile, we examined two types of amphiphilic systems: (I) cationic cetyltrimethylammonium bromide (CTAB) and SNP, and (II) anionic sodium dodecylsulfate (SDS) and SNP. Each system contained three different sizes of SNP. The current study attempts to answer the following questions: how does the presence of SNPs affect foam properties in flotation? Do the two systems acted synergistically or antagonistically with respect to foam stabilization? What are the effects of different size of SNPs on the foam properties?

2. Experimental

2.1. Materials

Spherical silica nanoparticles (SNPs) with three different sizes (20, 100 and 500 nm) were purchased from Shanghai Macklin Biochemical Co., Ltd., China. Their hydrodynamic diameters and zeta potentials were measured using a Zetasizer (Nano-ZS90, Malvern Instruments Ltd., UK). Additionally, their contact angles were measured with sessile drop method using a contact angle meter (DAS30, KRÜSS, Germany) [14]. The measured values are shown in Table 1.

CTAB, SDS, NaOH and HCl were supplied by Tianjin Chemical Reagent Co. Ltd., China. All reagents were analytical grade. Ultrapure water was used in all the experiments and it was obtained by using a Millipore Milli-Q system from Barnstead International, Dubuque, IA, USA. Glass containers were cleaned with ultrapure water before use. Experiments were conducted at room temperature unless specified otherwise.

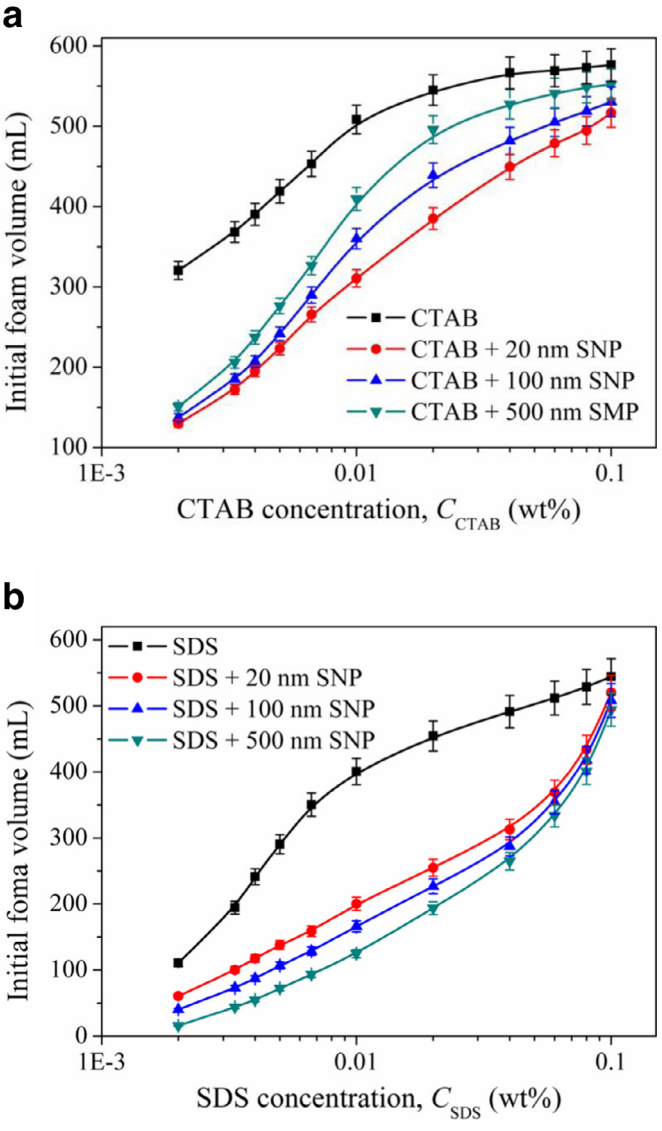

Fig. 1. (a) Foamability versus CTAB concentration for CTAB solution and CTAB/SNPs dispersions; (b) foamability versus SDS concentration for SDS solution and SDS/SNPs dispersions.

2.2. Preparation of CTAB/SNPs and SDS/SNPs dispersions

Firstly, each of the three kinds of SNPs was dispersed in ultrapure water and then treated by an ultrasonic cleaner (SK3200H, Shanghai Kudos Ultrasonic Instrument Co. Ltd., China) for 40 min to obtain a highly dispersed suspension. The concentration of SNPs was fixed at 0.1 wt% in all of the experiments unless specified otherwise, to avoid the formation of agglomeration. Subsequently, different concentrations of CTAB or SDS solutions were prepared by dissolving them in ultrapure water. These solutions were then added to the SNP dispersion dropwise under continuous stirring, to make the dispersions homogeneous. After that, dispersions were

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