International Journal of Mineral Processing 137 (2015) 64–70

Contents lists available at ScienceDirect

International Journal of Mineral Processing

journal homepage: www.elsevier.com/locate/ijminpro

Flotation of quartz particles assisted by nanobubbles

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A R T I C L E I N F O

Article history:
Received 16 December 2014
Received in revised form 26 January 2015
Accepted 18 February 2015
Available online 20 February 2015

Keywords:
Fine flotation
Nanobubbles
Size-to-size quartz recoveries

A B S T R A C T

Experimental studies of flotation of quartz particles, under various conditions and cells (setups), are presented. Pure and well-characterized quartz samples were treated with a commercial alkyl ether monoamine as flotation collector with bubbles in various sizes: coarse bubbles (400–800 μm); nanobubbles (200–720 nm); and their mixtures. The nanobubbles were generated by selective separation from microbubbles, which are formed together after depressurizing-cavitation of the saturated water in air (as in pressure flotation or dissolved air flotation), at 66.1 psi saturation pressure. Flotation with single nanobubbles was not effective due to their very low lifting power or practically nil buoyancy. Yet, size-by-size flotation recoveries with coarse plus nanobubbles, compared with coarse bubbles, enhanced by 20–30 % the very fine quartz fractions by 20–30% (8–74 μm; Sauter diameter—D_{32}) and slightly lowered the recoveries of coarse particles (67–118 μm; D_{32} diameter). Flotation of quartz samples (composites) having wide particle size distribution and results in a mechanical cell validated the overall recovery enhancement of the fines. Fine particle capture (nanobubbles enhanced the contact angle of quartz) and aggregation of the quartz ultrafines (proved with micrographs) by the nanobubbles are the main mechanisms responsible for the higher recoveries. The effect on flotation of the coarser quartz fractions, at bench scale, may be explained in terms of a reduced rising velocity of the coarse bubbles, in the presence of nanobubbles, decreasing the degree of bubble carryover. It is expected that the use of collector-coated nanobubbles (tailor-made "bubble-collectors" and flocculants) will broaden options in fine mineral flotation. The future sustainable forms (cheaply produced) of nanobubble generation on a large scale and their injection in cells are envisaged.

1. Introduction

Basic and applied research involving nanobubbles, namely generation forms, basic studies, and applications is, by far, one of the fastest growing areas nowadays (Hampton and Nguyen, 2010; Ohgaki et al., 2010; Agarwal, 2005; Attard et al., 2002; Attard, 2003; Ushikubo et al., 2010; Weijs and Lohse, 2012; Zimmerman et al., 2011). Today, many physical, biological, and chemical unique properties and high technological potential of the nanobubbles have been envisaged (Takahashi, 2005; Zimmerman et al., 2011; Fan et al., 2010a, 2010b, 2010c, 2012; Sobhy, 2013; Sobhy and Tao, 2013a, 2013b; Calgaroto et al., 2014; Rahman et al., 2014).

Despite the literature on nanobubbles becoming vast, nanobubble interfacial properties and their applications in many areas, including ore flotation, are interesting areas to explore (Zimmerman et al., 2011; Hampton and Nguyen, 2009; Ohgaki et al., 2010; Takahashi, 2005; Najafi et al., 2007; Weihong et al., 2013; Calgaroto et al., 2014).

It is believed by a number of authors (Hampton and Nguyen, 2009; Attard, 2003; Schubert, 2005) that dissolved gases accumulate preferentially at the hydrophobic solid–water interface, and this fact has been revealed by the atomic force microscopy (AFM) (Attard, 2003; Fan et al., 2013; Hampton and Nguyen, 2010).

One of the major (and old) technical challenges in the area of mineral processing is the recovery of the fine (<37 μm) and ultrafine (<8–13 μm) mineral particles by flotation. Most flotation feeds are composed of a wide particle-size distribution, and flotation cells should have a wide bubble-size distribution, including fine bubbles catching the fine particles (Yoon, 2000a, 2000b; Rubio et al., 2003; Zhou et al., 1997; Rodrigues and Rubio, 2007). Unfortunately, this does not occur in practice and the flotation cells, available in the market, do not provide the required bubble-size distribution (Franzidis and Manlapig, 1999; Phan et al., 2003; Yoon, 1999, 2000a, 2000b). Thus, the earlier problem of recovering the fines and especially the ultrafines (<8–13 μm) by flotation still continues (Sivamohan, 1990; Subrahmanyan and Fossberg, 1990; Feng and Aldrich, 1999; Szatkowski and Freyberger, 1985; King, 1982; Gontijo et al., 2007; Jameson et al., 2007; Tao, 2005).

Flotation devices, namely Jet (Jameson) flotation cell and "Microcel" type column, claim that a substantial amount of bubbles <600 μm is generated and, consequently, they should, in principle, be more suitable for fine particle recovery (Jameson and Manlapig, 1991; Honaker and Mohanty, 1996; Yoon and Luttrell, 1994; Jameson et al., 2007). The generation of fine bubbles in a hydrodynamic cavitation tube and in

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http://dx.doi.org/10.1016/j.minpro.2015.02.010
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columns (microbubbles injected) has been reported, claiming improvements in the flotation performance of fine fractions (Zhou et al., 1997, 1994, 1997; Honaker et al., 1996; Rubio et al., 2003; Yoon, 1993, 1999, 2000a, 2000b; Franzidis and Manlapig, 1999; Hieskanen, 2000).

In addition, a number of recent studies have reported some advantages in mineral flotation in the presence of nanobubbles (Fan and Tao, 2008; Fan et al., 2010a, 2010b, 2010c, 2013; Rahman et al., 2014; Sobhy, 2013; Sobhy and Tao, 2013a, 2013b).

The main claims are as follows: i. The nanobubbles would increase the contact angles and, subsequently, enhance the probability of flotation (coal, phosphates), mainly the bubble–particle attachment and stability (Fan and Tao, 2008; Fan et al., 2012; Sobhy, 2013); ii. Nanobubbles would enhance particle flotation recoveries of coal particles at lower collector and frother dosages and at high kinetic flotation rate (Fan et al., 2012; Sobhy, 2013; Sobhy and Tao, 2013a, 2013b); iii. The higher flotation recoveries would be not only in the fine particles but also in the coarser coal fractions (Fan and Tao, 2008; Fan et al., 2012); iv. The presence of nano-, jointly with micro- and coarse bubbles, increased the recovery of ultrafine particles of chalcopyrite with further advantages of using less collector and frother consumptions and lower power consumption.

The formation and separation (by splitting off from microbubbles) of a fraction of nanobubbles during depressurization of saturated air (66.1 psi), in water (as in DAF—dissolved air flotation) have recently been reckoned, and some physical and interfacial features were studied (Calgaroto et al., 2014). Stable (charged or not) nanobubbles are formed after the rapid depressurization of the dissolved air, and highly charged nanobubbles of a known size can be obtained either by modifying the pH or by introducing ionic surfactants (collector-coated nanobubbles). Accordingly, the sizes of the nanobubbles (200–720 nm) can be modulated by changing medium pH, and presented an isoelectric point, at about pH 4.5.

This is a continuation of the work by Calgaroto et al. (2014) on the potential application of the nanobubbles in flotation showing the results of assisted flotation of quartz at different size fractions and collector concentrations, with an injection of nanobubbles (150–350 nm), in mixtures with coarse bubbles (400–800 µm).

2. Experimental

2.1. Materials

Quartz powder was prepared from Brazilian quartz crystal rock by roll crushing (100% <1 mm) and ball milling (dry, autogenous operation), cleaning (50% v/v HCl, rinsing with distilled/deionized water), drying (24 h at 373 K), and mixing (tumbling) thoroughly. The final powder material was stored in clean plastic bags, each containing 50 g, until use for air flotation experiments (Englert et al., 2009). The quartz particles were fractioned using Mesh Tyler sieves, and the particle-size distribution of each fraction was measured using a Cilas 1064 laser particle size analyzer. Table 1 shows that the mean Sauter diameter D_{32} (surface-volume) varied between 8 and 128 µm.

Table 1
Quartz particle size analysis in terms of mean diameter (D_{50}) and mean Sauter diameter (D_{32}).

Sieve size, mesh Tyler	Mean diameter (D_{50}), µm	Mean diameter Sauter (D_{32}), µm
>65	266	128
>100	200	110
>200	120	65
>400	58	34
<400	16	8

Table 2
Flotation of quartz particles. Preparation of composite samples.

Siever size, mesh Tyler	Siever size, µm	Composite sample 1 mass percentage, %	Composite sample 2 mass percentage, %
>65	>212	20	40
>100	<212	20	40
>200	<150	20	10
>400	<75	20	5
<400	<37	20	5

2.1.1. Composite samples

Two different composite samples of quartz particles were prepared by blending all the previously separated fractions. Composite sample 1 had equivalent amounts of all fractions (20% of each fraction), and composite sample 2 was made up using different amounts of each fraction, as shown in Table 2.

2.1.2. Chemicals

Flotigam EDA 3B (Clariant®), a commercial flotation quartz collector that corresponds to an alkyl ether monoamine, with chemical formula $R–O–(CH_2)_3–NH_2$, partially neutralized with acetic acid (Clariant®, Technical Bulletin, Div. Functional Chemicals/Mining). NaOH and HCl, from Vetec®, were used for pH adjustments (kept between pH 6.8 and 7.2). Deionized water was used throughout the flotation work.

2.2. Methods

2.2.1. Generation of coarse bubbles

Here, coarse bubbles corresponded to bubbles generated by passing air through a fritted glass plate. The diameter of bubbles (measured photographically) varied between 0.4 and 0.8 mm with an air flow rate of 0.1 $L \cdot min^{-1}$ in the presence of 10^{-4} M Flotigam EDA 3B.

2.2.2. Generation of nanobubbles

The bubbles were generated by depressurizing air-saturated water solutions at a high flow velocity through a steel needle valve (2-mm internal diameter: Globo 012 — Santi®) into an empty glass column (50 cm high; 2 cm inner diameter). The saturation of air in water was achieved in a steel vessel containing an internal glass container with a height of 15 cm, an inner diameter of 12 cm, and a wall thickness of 1 cm. The container had a height of 14 cm, an inner diameter of 10 cm, a wall thickness of 0.5 cm, and a real capacity of 0.7 L (Calgaroto et al., 2014).

The depressurization followed by cavitation occurred, and both micro- and nano-bubbles are generated. Thus, a procedure was carried out by simply leaving the microbubbles levitate and abandoning the glass column, for 3 min (Fig. 1). Then, getting profit that nanobubbles are very stable, a sampling volume of 150 mL was bypassed from the column feeding the Zeta Sizer Nano ZS (red badge) – ZEN3600 – Malvern® Instrument to measure their average size.

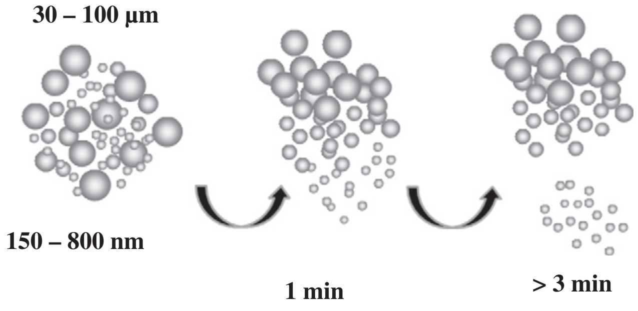

Fig. 1. Separation by uprising of the microbubbles, from mixtures with nanobubbles.