Minerals Engineering 121 (2018) 90–99

Contents lists available at ScienceDirect

Minerals Engineering

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

Kinetics of froth flotation of naturally hydrophobic solids with different shapes

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ARTICLE INFO

Keywords:
Flotation
Bubble attachment
Kinetics
Hydrophobicity
Frother
Particle shape
Polystyrene

ABSTRACT

In this paper, kinetics of flotation of naturally hydrophobic polystyrene platelets with the same roundness, solidity, surface roughness and hydrophobicity but different basic shapes i.e. circular, square and triangular, were studied in pure water and aqueous solutions of non-ionic frother. It was found that the flotation kinetics, and thus bubble attachment, were influenced by the particle shape. The flotation kinetics was the slowest for circular platelets, and then increased with decrease in the surface ratio, defined as the ratio of surface area of circular particle-to-surface area of investigated platelet. The results also showed that at above a certain frother dose, the bubble attachment time and inversed flotation rate constant for all investigated particles increased. The mechanism of this prolongation of time of flotation and bubble attachment to the solid surfaces due to the frother overdosage was presented and discussed. The influence of particle roughness on kinetics of bubble attachment and flotation was analysed and discussed as well.

1. Introduction

Flotation is a physicochemical process commonly used for upgrading of ores and other materials. A flotation process is used to separate valuable substances from unwanted ones utilizing differences in their surface properties. Generally, in flotation hydrophobic substances having the water contact angle greater than zero (Nguyen and Schulze, 2004; Kowalczuk and Drzymala, 2016), attach to gas bubbles, form stable particle-bubble aggregates and move upwards to either the froth layer (froth flotation) or the liquid/gas interface (film/skin flotation) where they are collected as a concentrate. The hydrophilic or slightly hydrophobic substances do not attach to gas bubbles and sink.

Flotation is a complex process and its complete description is very difficult because it may require more than 100 parameters (Drzymala, 2007; Wills and Finch, 2016). The efficiency of flotation depends on many parameters including: (*i*) properties of floating substances, that is their surface morphology, which includes their size, shape, hydrophobicity, roughness and crystal structure; (*ii*) type, construction and hydrodynamics of flotation devices; (*iii*) mode of work, including type and dose of flotation reagents, surface tension of liquid, size of gas bubbles, pH, electrochemical potential of solution and many others. Any change in flotation parameters can influence the whole process. Therefore, the selection of proper parameters is crucial to make the process highly effective both in laboratory and industrial scales.

Several studies have shown that the morphology of solids has the crucial effect on their flotation response (Table 1). Most papers have been devoted to flotation of glass beads and industrial minerals such as talc, wollastonite and quartz. The irregular particles have been usually produced by grinding the regular ones. It was found that ground particles having irregular shapes and sharp edges floated better as well as had shorter attachment time and higher flotation recoveries in comparison to regularly shaped particles (e.g. Koh et al., 2009; Vizcarra et al., 2011; Hassas et al., 2016; Xia, 2017). The asperity size strongly influenced the kinetics of flotation and bubble attachment. In the literature, the particle shape and roughness have been usually investigated together, and their individual effect on the kinetics of flotation, and thus bubble attachment, is difficult to distinguish. Only Guven and Celik (2016) investigated the effect of shape factor and roughness independently to identify their individual effect on flotation of ground glass beads in the presence of a collector.

Shen et al. (2002) and Pita and Castilho (2017) showed that the flotation selectivity of different types of plastics with either the same or different particle sizes was mainly dominated by the frother concentration, critical surface tension of wetting, contact angle, particle

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https://doi.org/10.1016/j.mineng.2018.03.006
Received 20 November 2017; Received in revised form 19 January 2018; Accepted 11 March 2018

Table 1
Selected examples showing the effect of particle shape on flotation.

Type of material	Particle size	Effect on flotation or induction time	Reference
Anthracite coal	0.25–0.5 mm	Particles with lower roundness floated quicker. No difference in ash content.	Wen and Xia (2017)
Glass beads	106–150 μm	Ground beads with sharp edges floated better and had shorter attachment time and higher flotation recoveries.	Hassas et al. (2016)
	75–150 μm	Blasted quartz particles with more angular and rougher surfaces gave better floatability compared to un-blasted particles.	Guven et al. (2015)
	75–90 μm	Shorter induction time for angular particles.	Verrelli et al. (2014)
	38–150 μm	Particles with higher elongation and flatness had higher recoveries.	Koh et al. (2009)
Talc	45–250 μm	Particles with lower roundness, higher elongation and flatness were more hydrophobic. The critical surface tension of wetting, and thus wettability, increased with increasing surface roughness.	Yekeler et al. (2004)
Quartz	75–250 μm	Ground particles in rod mill, with higher roughness and elongation had higher floatability. Surface roughness had greater influence on flotation than shape.	Rahimi et al. (2012)
Mica, vermiculite, wollastonite, talc	$d_{80} < 38\,\mu m$	Entrainment of particles of high aspect ratio was greater compared to relatively spherical particles for similar sizes.	Wiese et al. (2014)
Alumina	74–106 μm	Angular particles had higher flotation recoveries.	Guven et al. (2016)
Plastic	1.0–5.6 mm	Among particles with similar wettability, irregular (lamellar) particles exhibited better floatability than round ones.	Shen et al. (2002) and Pita and Castilho (2017)
Ink		Spherical ink particles attached faster to the bubbles than irregular particles	Schmidt and Berg (1997)

Table 2
Commonly used expressions for shape properties. *A* – area, *P* – perimeter, *L* – length, *W* – width, *V* –volume, *d* – equivalent of nominal diameter, *S* – surface area.

Shape factor	Formula
Circularity f_{circ}	$4\pi A^2/P$
Elongation ratio *ER*	L/W
Roundness *R*	$4\pi A/P^2$
Aspect ratio *AR*	W/L or $1/ER$
Elongation	1-W/L or 1-AR
Shape factor	Thickness/(breadth · length)$^{1/2}$
Convexity ratio	Area/convex area
Fullness ratio	(area/convex area)$^{1/2}$ or (convex ratio)$^{1/2}$
Sphericity ψ	$6\,V/d{\cdot}S$
	$A^{-1}{\cdot}(36\pi V)^{1/3}$
	(thickness · breadth)$^{1/3}$/(length)^2
	area of equivalent sphere/measured surface area

density and shape. Among particles with similar wettability, irregular (lamellar) particles exhibited better floatability than round ones. However, in these studies only one shape within the same plastic type was investigated and roughness was not taken into consideration. There are also limited studies, which investigated independently the influence of particle shape and roughness on flotation of naturally hydrophobic solids in pure water and only frother (collectorless flotation). Therefore, in this paper we examine the influence of particle shape with the same solid type, hydrophobicity, roundness, solidity and surface roughness. The regular particle shapes, that is circular, triangular (equilateral) and square platelets were stamped from the same 1 mm thick polystyrene (PS) sheet, which made ~~it~~ possible to investigate independently the effect of shape factor and roughness on flotation kinetics of naturally hydrophobic PS in the presence of non-ionic surfactant. Moreover, the single bubble tests were conducted in order to show the influence of particle surface roughness and frother concentration on kinetics of three-phase contact (TPC) formation and bubble attachment.

2. Materials and methods

2.1. Materials and surface analysis

Polystyrene (PS) platelets with the similar size and mass but different basic shapes i.e. circular, square, triangular, were stamped from a 1 mm thick PS sheet. The shape factors of PS platelets were determined based on images obtained with a Nikon SMZ745T stereo microscope, collected by use of the NIS Elements D 4.5 software and analysed by the Image J 1.42I analysis software. The platelets size and shape factor parameters such as width, height, Feret mean diameter, roundness, surface area (SA), perimeter and solidity were automatically calculated by the software utilizing the formulas given in Table 2. Width was defined as the width of the smallest rectangle enclosing the particle (bounding rectangle), which is parallel to the x- and y-axes and defined with the length parameters in the x- and y- directions. The surface ratio was calculated as: the surface area of circular platelet-to-surface area of investigated platelet. For circular platelets the surface ratio was equal to 1.00 and decreased with the surface area. Size and shape factors of investigated platelets are listed in Table 3.

The thick PS sheet was used as received without any surface modification. Both sides of the PS sheets were investigated as differences in surface roughness of each of the them were noticeable. To visualize the differences in roughness of prepared solid surfaces, the so-called “focus-stacking microphotography” approach was used. The degree of roughness of the plates was estimated on the basis of image analysis (ImageJ 1.49v) of the photos taken using a light microscope (Nikon Epiphot 200). A stack of micrographs taken at different focal positions (evenly spaced intervals into the depth of field) was merged into a single, entirely focused composite image. Then, the micro-images in the series were transferred to a PC and stitched together using the ImageJ Extended Depth of Field algorithm (Aguet et al., 2008). The 3D image of the solid surface was obtained on the basis of differences in the final image grey-scale, which was automatically recalculated into the topography variations, using the Interactive 3D Surface Plot plugin. Therefore, only the x-y axis dimensions had physical meaning, while in z-direction the topography information had only the qualitative character.

A non-ionic frother i.e. tri(propylene glycol) butyl ether (C_4P_3, $C_4H_9(OC_3H_6)_3OH$) was purchased from Sigma Aldrich and it was of the highest available purity (≥99%). Aqueous solutions of C_4P_3 were prepared by using pure water. Distilled water of pH = 5.8 ± 0.2 and specific conductivity of 10^{-6} S/cm was used in cleaning and preparation of frother solutions for flotation, while Mili-Q water® was used in single bubble tests, surface tension and contact angle measurements.

2.2. Flotation tests

Flotation tests were performed in a Denver D12 flotation machine with a stainless-steel cell of volume 1.5 dm^3. The prepared platelets, referred further also to PS solids or particles, were washed in a large amount of warm distilled water. The known amount of PS platelets (usually 100 pcs) were added to the clean flotation cell together with 1.35 dm^3 of either pure water or non-ionic frother (C_4P_3) solution of known concentration, and then conditioned for 4 min without air