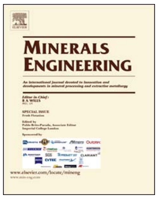
Minerals Engineering 110 (2017) 139–144

Contents lists available at ScienceDirect

Minerals Engineering

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



Residence time distribution measurements and modelling in industrial flotation columns

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ARTICLE INFO

Keywords:
Residence time distribution
Column flotation
Mixing regime
Modelling
Industrial measurements

ABSTRACT

This paper presents the results of measurements and modelling the residence time distribution (RTD) in industrial flotation columns from several plants, using radioactive and salt tracers. Columns under study had different geometry (*i.e.* square, rectangular and circular transverse sections) and size (from *ca.* 2.5 m^3 to 180 m^3). Data were obtained for liquid (both radioactive and salt tracers), floatable and non-floatable solids by size classes (radioactive tracers). Model structures including the axial dispersion, perfect mixer (PM), large and small tanks in series (LSTS) and two parallel perfect mixers were evaluated and compared. Based on the results, it is concluded that the mixing regime in flotation columns cannot be described by a unique model structure nor can they be related to the cross-sectional area or size of the columns.

All industrial datasets presented in this paper showed poor fitting with the perfect mixer model. On the other hand, the LSTS as well as the two parallel perfect mixers models were outstandingly flexible compared to the other structures.

The tests allowed the identification of the flow regime and the effective residence times of the different phases, which ranged from 9 to 41 min. The RTD characterization has been useful to detect process failure such as bypass flow identification as well as unbalanced flow distributions in parallel columns at industrial scale.

1. Introduction

Since its commercial introduction in 1980, columns have emerged as important devices in the flotation process. Some of its distinctive features are generation of fine bubbles, countercurrent bubble-slurry flows, thicker froth height and the use of cleaning water (Finch and Dobby, 1990). These characteristics make column flotation especially suitable for cleaning stages, although there are also some concentrators that use it in rougher stages (Massinaei et al., 2007). The lack of moving components, easy access to service parts and therefore low operating and maintenance costs, give column flotation additional advantages (Finch, 2016). In the absence of an impeller, the mixing in columns –and resulting contact between particles and bubbles– is mainly due to pulp recirculation and the turbulence due to bubble motion (Yianatos et al., 2005).

The fluid dynamic characterization of column flotation is important for the diagnosis and optimization of existing equipment and for the design of more efficient (or larger) machines. An important feature, the residence time distribution (RTD), can be defined as the probability density function that gives the time an element spends inside a tank in a continuous flow system. Residence time distribution arises from a complex interaction between the profile velocity, diffusion and turbulence, and it greatly influences the metallurgical performance of flotation (Pal and Masliyah, 1990; Rice et al., 1981; Yianatos et al., 2015).

Tracer studies allow the description of residence time distribution curves and its utilization for system analysis (Reed, 1986). The most used methodology for RTD determinations consists of the injection of a small mass of tracer, the “impulse”, at the system inlet and then measuring its concentration at the output. The impulse must be as close to a Dirac Delta function as possible. A way to approach this is by injecting the tracer and producing a function significantly shorter than the residence time of the actual system.

For reliable measurements, the tracer must not (1) interact with the other phases in the system, (2) modify the properties of the fluid or (3) disturb the hydrodynamics of the system. Desirable tracer characteristics include (1) to have behaviour similar to the material under investigation (*i.e.* possessing similar physical and chemical character-

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http://dx.doi.org/10.1016/j.mineng.2017.04.018
Received 31 January 2017; Accepted 26 April 2017

istics); (2) to be easy and unambiguously detected; and (3) to produce minimal disturbance to the system (Bjornstad, 1991). Thus, radiolabeling become an ideal technique especially when it comes to characterizing a process involving three phases such as flotation (*i.e.* liquid, solid and gas).

Radiotracers have been used for RTD determination in a broad spectrum of applications at both pilot and plant scale (Din et al., 2010; Dagadu et al., 2012; Kim et al., 2005; Sharma et al., 2016; Pant and Yelgoankar, 2002; Yianatos et al., 2008a; Yianatos et al., 2013). This technique allows online measurements of several regions of a tank without disturbances produced by sampling. From these experiments, relevant flotation characteristics can be determined such as entrainment factors (Yianatos et al., 2009); flow patterns of liquid and solids in several size fractions (Lelinski et al., 2002); flotation kinetics in continuous operation (Yianatos et al., 2010); among others.

Modelling RTD of real systems involves calculation of parameters from different model structures such as axial dispersion (*e.g.* the dispersed plug-flow model), or arrangements of different types of flow elements such as dead zone, perfect mixer and plug flow (*e.g.* the mixed models) (Reed, 1986). The latter are reported to be more flexible, since each flow element can be individualized and parameterized (Finch and Dobby, 1991). However, very complex arrangements having a large amount of parameters may result in misleading information or over-parameterization. Yianatos et al. (2005) applied a mixed structure based on large and small tanks in series (LSTS) to model full-scale flotation columns (*ca.* 2.5–180 m^3). More recently, an arrangement based on two perfect mixers in parallel with dead time allowed modelling of industrial mechanical cells (Yianatos et al., 2014). These schemes presented an adequate trade-off between flexibility and number of parameters.

This paper presents RTD of industrial flotation columns from 7 different plants. Solid and liquid RTD data were recorded using both radioactive and saline tracers. The RTD were fitted to four model structures including: (1) the axial dispersion model (ADM), (2) the classical perfect mixer (PM), and two multi-stage models, namely (3) LSTS and (4) two parallel perfect mixers. The higher flexibility of the two latter allowed the description of the mixing regime in industrial flotation columns while keeping a low number of parameters.

2. Experimental procedure

2.1. Column description

The RTD measurements were performed in seven different concentrators (A-B-C-D-E-F-G). Column flotation characteristics are shown in Table 1. A total of 28 RTD curves from rectangular, square and circular columns were analysed.

2.2. Radioactive tracer technique

The radioactive tracer technique was used to determine the RTD in columns from plants A, B, C and D (Table 1). Since the half-life of tracers must be compatible with the typical mean residence times in flotation columns, the radioactivity type and intensity were determined considering the pulp flowrates and fluid characteristics. This allowed for real-time RTD measurements (Díaz et al., 2013).

Table 1
Column flotation characteristics.

Plant	Shape	Side or diameter (m)	Height (m)	Number of measurements
A	Rectangular	2 × 6	13	2
B	Square	1.8 × 1.8	13	3
C	Circular	4	14	11
D	Circular	0.91	12	5
E	Rectangular	2 × 6.5	14	1
F (column 1)	Square	0.45 × 0.445	12	3
F (column 2)	Square	0.91 × 0.91	12	2
G	Circular	2.5	13	1

Table 2
Radioactive tracers.

Plant	Floatable solid	Non-floatable solid	Liquid	Size class
A	–	Na-24	Br-82	–
B	Cu64	Na-24	Br-82	–
C	–	–	Br-82	–
D	–	Na-24	Br-82	Sc-46 (Fine, medium and coarse)

Br-82 as ammonium bromide in solution was used as liquid tracer (half-life of 36 h). Floatable and non-floatable solids were sampled from the concentrate and tailings of the flotation circuits, respectively. The solid samples were chemically assayed for element detection in order to produce radioisotopes by gamma neutron activation. The activated components were Cu-64 for floatable solids (half-life of 12.8 h), Na-24 for non-floatable solids (half-life of 15 h) and Sc-46 (half-life of 84 d) for solids by size class. Radioactive tracers used in the industrial tests are summarized in Table 2.

The way the tracer is injected into the feed is critical to generate a pulse signal. A pneumatic system of high reliability has been developed to introduce a small amount of radioactive tracer (around 100 mL of liquid or pulp with solids) at the column feed (Yianatos and Díaz, 2011). The response time of the radioactive tracer was then measured on-line using non-invasive sensors located directly at the outlet stream of the flotation columns, as shown in Fig. 1. Activity was measured by scintillating crystal sensors of NaI(Tl) of 1″ × 1.5″, Saphymo Srat. The local background was registered and subtracted from the data to obtain the actual tracer radiation. In each experiment, the normalized radiation intensity was determined to evaluate the mean residence time.

2.3. Saline tracer technique

Saline tracers (*i.e.* NaCl or LiCl) were used to estimate the RTD of the liquid phase in columns of plants E, F and G. This technique consists of injecting an amount of saline solution (close to an impulse) at the inlet of the column and measuring the ion concentration in column streams. Discrete samples of the feed, concentrate and tails were taken after the tracer injection. This way of sampling limited the number of data points that can be obtained for the determination of RTD.

Sodium chloride concentration was determined by means conductivity measurements. Prior to the introduction of the tracer, a measurement of the electrical conductivity inside the column was taken. After the tracer was introduced, the evolution of concentration over time was evaluated. The conductivity measurements obtained were corrected by subtracting the initial value. Conductivity was then transformed to concentration using a calibration curve.

When LiCl was used, atomic absorption spectroscopy (AAS) was performed to measure lithium concentration. Because of the high sensitivity of AAS and the fact that the analysis specifically targets the tracer (unlike conductivity measurements), the injected LiCl mass was markedly smaller in comparison to NaCl. In addition, the low concentration of lithium at the inlet stream favoured tracer detection in the outlet stream (Yianatos et al., 1987). Natural salt concentration at the inlet of the columns was registered and subtracted from the data to obtain the actual tracer concentration.

Table 3 summarizes feed flowrate, saline tracer type, mass and solution volume used in each plant. The amount of saline tracer was chosen as a function of the feed flowrate to produce a significant concentration at the column outlet, according to the associated measurement technique (conductivity or AAS). The highest volume of