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Column flotation simulation: A dynamic framework

Jocelyn Bouchard [a,b,*,1,2], André Desbiens [a,c,1], René del Villar [a,b,1]

[a] LOOP – Laboratoire d'observation et d'optimisation des procédés, Université Laval, Pavillon Adrien-Pouliot, Quebec City, Québec G1V 0A6, Canada
[b] Département de génie des mines, de la métallurgie et des matériaux, Université Laval, Pavillon Adrien-Pouliot, Quebec City, Québec G1V 0A6, Canada
[c] Département de génie électrique et de génie informatique, Université Laval, Pavillon Adrien-Pouliot, Quebec City, Québec G1V 0A6, Canada

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ABSTRACT

Since the introduction of column flotation in mineral processing plants in the early 1980s, modelling of this process has become a prevailing field of investigation. Even if significant progresses have been made with every new attempt, most of the proposed models or simulators have been restricted to the steady-state behaviour. When dynamic mass balance equations were considered, a constant pulp level during the simulation was always assumed. The objective of this paper is to present a framework for the fully dynamic simulation of column flotation. The emphasis is placed on the simulation of water, solids and gas flows and their effect on the pulp level and output flow rates.

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1. Introduction

Since their introduction in mineral processing plants, flotation columns received considerable attention from academics and practitioners. Work related to modelling, especially for the mixing conditions and steady-state performance, led to a better understanding of design and operation issues. Some interesting advances have also been made on column flotation simulation. Although practical outcomes for the mineral processing community have yet not been as tangible, they are progressively emerging, for instance with the work of JKTech (Bouchard et al., 2009).

Pioneering efforts started in the eighties. Luttrell et al. (1987) proposed a static simulator based on a population mass balance (air bubbles, unattached solid particles, and bubble particle aggregates). Mass transport was considered in the model using fluid flows and particle buoyancy, while the bubble particle attachment rate was evaluated using first principles. Some processes, such as the bubble loading and mixing properties, were explained under pre-specified operating conditions, using a semi-fundamental approach requiring the calibration of two empirical coefficients. The simulator attempted to predict the recovery of a specific column flotation operation for design, control, optimisation and scale-up purposes.

During the same period, Sastry and Lofftus (1988) also developed a simulator using a similar approach, but considering the dynamic mass balance equations. The resulting tool opened the door to time-dependent investigations, and process control applications. The assumption of constant air and water holdups, along with the impossibility of analytically solving the general model, represented the greatest limitations of their work.

The addition of air and water mass balance equations to a five-well-mixed zone reactor instead of the three-zone model of Sastry and Lofftus (1988) led to more flexibility for the simulator proposed by Pate and Herbst (1989). Their approach also replaced the axially dispersed plug flow model with a distributed volume mixers-in-series estimation for increasing computational efficiency. The air mass balance was however taken into account on a static basis following the assumption that air holdup is subject to very fast changes compared with the water volume. Particles could be of any size and were divided into three classes: free valuable mineral, free gangue and locked. Similarly to the above-mentioned simulators, the proposed model exhibited certain empirical features regarding the calibration of rate constants and the description of some phenomena using correlations (water entrainment, water drainage, etc.). Later on, the same team used this dynamic simulator to design a methodology for selecting a control strategy for a column flotation unit (Lee et al., 1991).

Cruz (1997) made a further step and proposed a fully dynamic simulator of column flotation metallurgical performance. Based on fundamental considerations, her work included a comprehensive description of complex phenomena, such as bubble coalescence in the froth and bubble loading, and considered particle and bubble size distributions as well as a particle composition distribution. The design was based on the application of a population

* Corresponding author at: LOOP – Laboratoire d'observation et d'optimisation des procédés, Université Laval, Pavillon Adrien-Pouliot, Quebec City, Québec G1V 0A6, Canada. Tel.: +1 4186562554.

E-mail addresses: jocelyn.bouchard@gmn.ulaval.com (J. Bouchard), desbiens@gel.ulaval.ca (A. Desbiens), rene.delvillar@gmn.ulaval.ca (R. del Villar).

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Nomenclature

A	function
A_c	columnn cross section area
α	air recovery
β	distribution coefficient
C	frother concentration
C_c	contamination factor
C_d	drag coefficient
C_{pb}	viscous drag coefficient within Plateau borders
d	diameter
δ	relative volume of the variable pulp cell
ε	holdup
h	height
H	froth depth
H_I	interface position
I^*	position of the first phantom pulp cell
J	superficial velocity (Q/A_c)
J_b	water bias
J_{gs}	gas-slurry drift flux citep
k	kinetic rate constant
k_1	function
λ	function
$\boldsymbol{M}$	network matrix
μ	viscosity
ns	number of mineral classes
N_t	number of simulation cells
P	pressure
Q	volumetric flow rate
Q'_{g^*}	gas flow rate through the interface cell computed before applying the correction for the variation of interface position
Re	Reynolds number
ρ	specific gravity
R_v	average bubble radius in cm
$\boldsymbol{S}$	s vertical profile in a simulated flotation column: $\boldsymbol{S} = [s^1, s^2, \ldots]^T$
s	generic variable or Laplace variable
t	time
t_s	simulation period
U_{ps}	relative particle settling velocity
U_{bs}	terminal rising velocity of a single bubble
U_g	bubble rising velocity citep
U_{gs}	gas/slurry relative velocity
U_l	liquid interstitial velocity
U_p	particle interstitial velocity
V	volume
v_{pump}	tailings pump speed
v_g	vertical component of the froth velocity

Indices and superscripts

ap	aerated pulp
at	newly attached particles
atm	measured at atmospheric pressure
b	bubbles or bias
c	concentrate
cell	simulation cell with constant volume
e	entrained stream
ex	external
f	feed
fpos	position of the slurry feed port
fz	froth zone
g	gas
i	simulation cell position
I	interface
l	liquid
ld	liquid drifted
p	pulp or particles
pat	particle attachment rate
pd	particle drifted
pdet	particle detachment rate
phantom	phantom simulation cell
pz	pulp zone
ref	reference
r	returned stream
sb	solids attached to bubbles
s	solids or slurry
t	tails
w	water or wash water
wpos	position of the wash water feed port

balance to a vertically distributed volume mixers-in-series framework: a perfectly mixed aeration zone, a perfect-mixers-in-series lower collection zone, a single perfectly mixed feed zone, a perfect-mixers-in-series upper collection zone, the interface, and three plug flow volumes for the froth (stabilised froth, wash water addition zone, and draining froth). Notwithstanding improvements in column flotation simulation, the extent of potential control applications was significantly narrowed down by not allowing carrying out dynamic flow rate variations. In fact, operating conditions were fixed off-line and remained constant throughout the simulation. The process was then driven from an initial to a final state as defined by the simulated operating conditions. Gas holdup and solids flow rate changes were computed, but the dynamic variations of froth depth were not considered. Cruz nevertheless achieved a major breakthrough, even though this work did not attract much attention in the mineral processing community.

On a more specific basis, the froth physics issue was extensively studied by Neethling and Cilliers (2001, 2002a), Neethling et al. (2002), Neethling (2008), and more recently by Brito-Parada et al. (2012), who extended the model of Neethling et al. (2000) *to consider unsteady state in up to three dimensions*". The proposed computational fluid dynamics (CFD) model studies liquid drainage in foams from a description of the "*the balance of the gravity, capillary and viscous forces acting on the liquid in the Plateau borders in a flotation foam*".

For process control purposes, simulators may be explicitly used for two different aims:

1. nonlinear model-based control (NMC) and
2. real-time optimization (RTO).

The simulated process response is used in both cases for computing an objective function to be minimised. It must be emphasised that unlike RTO, NMC requires dynamic models.

According to Henson (1998), the use of commercial dynamic simulators for nonlinear predictive control had not yet been reported in the literature at the end of the nineties. The main reason explaining this is certainly that the complexity of the on-line solution of the nonlinear programming problem increases with that of the model, hence leading to computational and reliability difficulties. The unavailability of the model equations to the control designer is another factor that cannot be denied (Henson, 1998). However, Desbiens and Bouchard (2004) and Bouchard et al. (2005) presented novel predictive control formulations mitigating these obstacles, where the explicit minimisation of the cost function was replaced by a simulation.

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