Minerals Engineering 23 (2010) 117–124

Contents lists available at ScienceDirect

Minerals Engineering

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

Hierarchical hybrid fuzzy strategy for column flotation control

Felipe Núñez [a,*], Luis Tapia [b], Aldo Cipriano [a]

[a] College of Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile
[b] Superintendencia Concentradora, Compañía Minera Los Pelambres, Chile

ARTICLE INFO

Article history:
Received 13 March 2009
Accepted 3 November 2009
Available online 28 November 2009

Keywords:
Column flotation
Hierarchical control
Supervisory control
Expert systems
Fuzzy control

ABSTRACT

Column flotation is widely used in the concentration of low grade ores. Often column flotation concentrate is the final product of a very complex circuit, and therefore control of the metallurgical performance has direct impact in the plant performance. Several control schemes has been implemented for the stabilization of column flotation process, including decentralized control, model predictive control and fuzzy approaches, which attempt to control froth depth, water bias and air holdup. At the same time many efforts have been oriented to improve process instrumentation, with the aim of providing better measurements for control purposes. Instrumentation improvements have made feasible the design of strategies focused on recovery and concentrate grade control. In this work we present the design and implementation of a new advanced controller for column flotation process. The controller was implemented in a 10 columns cleaning stage following a hierarchical scheme with two control levels: an improving level with the aim of metallurgical performance control of the whole process, and a stabilizing level in charge of the distribution of control actions in each column. The controller design was made based on a hybrid scheme with three different operation scenarios, defined by a recovery–concentrate grade domain partition. Results show that the controller is able to keep the process in the normal operation scenario 80% of the analyzed time; on the other hand, when the process was operated only with local control it achieved the normal operation scenario 43% of the analyzed time. Results also show that the controller is capable of increasing concentrate grade and recovery mean values, despite variations on feed grade; while reducing recovery and concentrate grade standard deviations.

1. Introduction

Flotation columns are used in a large number of sulphide mineral concentrators, mainly in the cleaning stage. Flotation columns are long vertical vessels that are continuously fed with pulp of fine solid particles consistent in valuable minerals and gangue solid particles. Concentration by flotation in columns is achieved by the conditioning of the pulp with appropriate chemical reagents, the continuous air injection and the use of fresh water for concentrate washing (Finch and Dobby, 1990). Fig. 1 presents a simplified scheme of a flotation column.

In direct column flotation the valuable mineral particles are made to be hydrophobic so that they attach to air bubbles generated by air injection at the bottom of the column. The bubbles with attached particles go to the column top where they are recovered as the column overflow or floated product. Other particles should ideally remain (or be made) hydrophilic so that they remain in the pulp and then move downwards to the bottom leaving the column as an underflow. The addition of fresh wash water on the top of the column allows the cleaning of the froth zone by drainage of the hydrophilic particles entrained in the air bubbles. The cleaning action takes place when a downward flow of wash water, known as water bias, pass through the froth zone. During normal operation two distinct zones can be identified inside the column: collection zone, where the hydrophobic particles are collected by the air bubbles and the froth zone, constituted mainly by air bubbles, and collected particles (Finch and Dobby, 1990; Yianatos and Bergh, 1995; Finch et al., 2007). There are cases when the valuable mineral is recovered in the underflow, this is known as reverse flotation, or in other cases both overflow and underflow are valuable, and column flotation is used as a separation process. This work is focused on direct flotation and further details on different flotation schemes can be found in Finch et al. (2007).

Generally, wash water and air flowrates and froth depth are measured on line, and tailings, air and wash water flowrates are manipulated. On line grade analyzer measurements for feed, tailings an concentrate, tailings and feed flowrates and some others variables are often incorporated into the system when a supervisory control strategy is implemented on top of a distributed control system or a programmable logic controller (PLC).

The primary control objectives (or metallurgical objectives), as indexes of productivity and product quality of the whole process,

---

* Corresponding author.
E-mail addresses: fenunez@ing.puc.cl (F. Núñez), aciprian@ing.puc.cl (A. Cipriano).

0892-6875/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mineng.2009.11.002

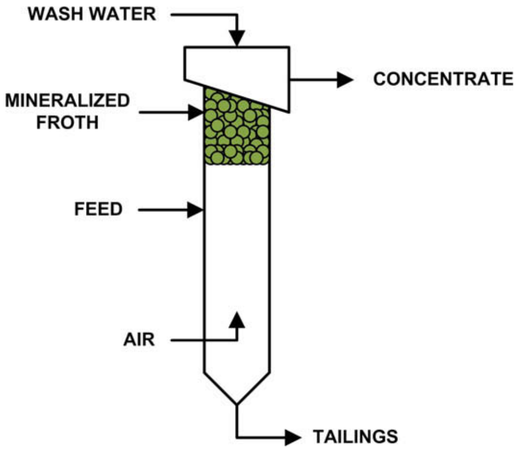

Fig. 1. Simplified scheme of a flotation column.

are the metallurgical recovery and the concentrate grade (Bergh and Yianatos, 1993; Finch et al., 2007). However, these objectives are often not directly controlled mainly due to limitations in process instrumentation (Bergh and Yianatos, 1993; Yianatos and Bergh, 1995) and the absence of accurate models capable of relating metallurgical performance with local variables (Bergh and Yianatos, 2003). A common practice is to control secondary objectives, such as pH at the feed, froth depth, air flow rate and wash water flow rate. These are usually implemented as local controllers. Ideally, when primary objectives are measured, the control strategy is to change the set points of the controllers, in order to achieve a good metallurgical performance (Bergh and Yianatos, 2003).

Recently, improvements in process instrumentation and information management have made feasible the design and implementation of control strategies focused on metallurgical objectives, yielding a hierarchical control scheme mainly based on heuristic models or expert systems (Bergh et al., 1995, 1998, 1999; Bergh and Yianatos, 2003).

In this paper we present an hybrid fuzzy strategy for column flotation metallurgical performance control, implemented in a hierarchical scheme on top of the plant distributed control system (DCS). The controller aim is to improve the concentrate grade keeping the metallurgical recovery over a minimum value, taking into account operational restrictions over the manipulated variables, and different operation scenarios obtained from a recovery–concentrate grade domain partition.

2. Control of flotation columns

Several control strategies for flotation columns has been developed in the last decades. The simplest control is the regulation of froth depth with tailing flowrate, and the manual regulation of air and wash water flowrates (Finch and Dobby, 1990; Bergh and Yianatos, 1993). This simple control strategy has demonstrated be sufficient for operation. However, for process performance improvement more elaborated control schemes are needed.

The primary control objectives are the column concentrate grade and recovery, which are indexes of metallurgical performance and product quality. The on line measurement and estimation of these variables usually requires sophisticated instrumentation and difficult maintenance and calibration processes. This fact has contributed to the design of a strategy known as stabilizing control (Bergh et al., 1995; Carvalho and Durão, 2002; Vieira et al., 2005) which attempt to control secondary objectives such as pH at the feed, froth depth, water bias and air holdup, as an indirect optimization of metallurgical performance.

Consequently, two main investigation lines have arisen: one dedicated to control of secondary objectives and an incipient one dedicated to control of metallurgical or primary objectives. In the stabilizing line, del Villar et al. (1999) discussed the control of bias and level in a laboratory column. Carvalho and Durão (2002) discussed the performance of a laboratory flotation column under fuzzy control for water bias, air holdup and froth depth, using tailings, wash water and air flowrates as manipulated variables. Carvalho and Durão (2002) also introduced the concept of hybrid controller, based on a fault tolerant scheme. When froth depth is outside the predefined domain, the conditions of the process are considered to be anomalous and the controller acts in emergency mode looking for a quick convergence of froth depth. Otherwise, i.e., when froth depth is inside the predefined domain, the controller acts in standard fuzzy mode. Vieira et al. (2005) proposed fuzzy modeling for flotation columns control obtaining a multivariable model with feed flow rate, which in normal industrial operation is considered a disturbance, wash water, air and tailings flowrates as inputs. The outputs of this model are froth depth, water bias and air holdup. Persechini et al. (2004) proposed a decentralized approach for froth depth, water bias and air holdup control based on a relative gain array analysis. The analysis resulted in a near identity matrix, which justify the decentralized scheme. Bouchard et al. (2005) discussed several control techniques for a pilot plant column, including decentralized PI, gain scheduling and multi model schemes. Núñez et al. (2006) tested a global predictive control scheme for froth depth and air holdup control in a pilot plant using softsensors for process variables estimation. Mohanty (2009) proposed an artificial neural network model for predictive control of froth depth in a pilot column. The stabilizing investigation line, has also focused in instrumentation improvement for control purposes (Sadr-Kazemi and Cilliers, 2000; Yianatos et al., 2001; Gomez et al., 2003; Bouchard et al., 2005; Núñez et al., 2006), however, the incorporation of these new instrumentation in industrial control strategies is still under development.

In the metallurgical investigation line, the improvement of X-ray analyzers and information management systems has permitted the design and implementation of more robust control schemes. Bergh et al. (1998) present a metallurgical controller tested by simulation, based on four coupled simulators capable of simulating metallurgical and dynamic behavior and local PID control loops. Bergh et al. (1999) discussed the design, implementation and evaluation of supervisory control for two rectangular 12 m^2 cross section and 13 m height flotation columns at Salvador industrial plant. The supervisory control is based on a fuzzy expert system in charge to control the metallurgical performance. To achieve that, concentrate grade is measured using X-ray analyzers and recovery is estimated based on grade measurements. The controller changes the set points of froth depth, air and wash water flowrates local controllers implemented in the plant distributed control system. Results obtained show an important standard deviation reduction for concentrate grade and robustness over feed grade variations.

The results presented in Bergh et al. (1999) demonstrate the potential of supervisory fuzzy logic based expert systems in metallurgical control. Recently, several commercial fuzzy logic based expert system applications have been installed in industrial plants, not only for flotation process improvement but also for grinding and crushing with variable success.

3. Industrial plant under analysis

The portion of the plant under analysis consist in ten cylindrical columns of 4 m diameter and 14 m height, working in parallel as