Chapter 1

Introduction

Since the invention of the column flotation process and its successful introduction in mineral processing plants, there has been a lot of interest in understanding the various mechanisms that take place during operation. Column flotation has been found to yield better performance than conventional flotation cells, particularly with fine particles. This improvement has to do with the flow conditions prevailing in the column, the washing down of hydrophilic material by the countercurrent liquid flow, the degree of froth stability and the column relative dimensions.

Achieving a good understanding of the intricacies of the process can only be realized after all the subprocesses involved are well examined. Research on column flotation mechanisms has a foundation in most of the studies performed on the conventional flotation operation. In spite of the differences, the vast amount of information available on general flotation provides the framework for the development of relationships applicable to column conditions. Studies on bubble-particle interactions, solid entrainment, extent of mixing, and froth stability and dropback in flotation columns have been widely published in the last two decades. Nonetheless, combining all this work into a general representation or model has presented significant challenges, especially due to the nature of the froth region.

There are, at present, several mathematical models that describe the collection of particles and the rise of bubbles under a range of conditions, from perfectly mixed to plug flow (Dobby and Finch, 1986a; Luttrell and Yoon, 1991; Ityokumbul, 1992; Alford, 1992). Most of these models consider the flotation of particles as first-order rate process, while a few others suggest a different order in the representation. Most of such mathematical models are intended to relate the recovery of mineral species, at steady state, to factors characteristic of the collection region. Such factors include the slurry residence time, mean bubble and particle sizes, and gas rate.

Nonetheless, an adequate dynamic model is highly desirable because of its potential applicability in optimization, control, and as a simulator for training and for testing different operating schemes. The dynamic models reported in the literature are being applied, along with modern control theory tools such as the Kalman filter estimator, in the development of model-based control strategies (Herbst, Pate and Oblad, 1992). However, there are problems connected to the stability of the dynamic equations, and some oversimplifications are normally done in order to obtain a numerical solution. Despite some attempts at incorporating the froth phase into a column-flotation dynamic model, important froth events, such as bubble coalescence and particle attachment and detachment, are normally not taken into account. Unfortunately, the behavior of the froth regions is a key element in the overall performance of the flotation column, particularly because of the cleaning that takes place through detachment and reattachment. Froth residence time, stability and mobility are all characteristics that need to be included in a complete column flotation model.

Some theoretical analyses of the phenomena taking place in a three-phase froth have been reported (Dippenaar, 1982a; Subrahmanyan and Forssberg, 1988; Johansson and Pugh, 1992; Szatkowski, 1995), but the complexities and nature of the parameters render the task of obtaining a mathematical representation very challenging. Other attempts at describing the froth region characterize the processes in the froth using first-order rate constants (Harris and Rimmer, 1966; Mika and Fuerstenau, 1969; Moys, 1978; Ross and van Deventer, 1988; Yianatos et al., 1988). Thus, there is a rate constant for entrainment and another for detachment. Unfortunately, determination of these rate constants offers several complications, particularly in industrial columns. A number of investigations rely on available two-phase froth models that are descriptive of cellular foams (Yianatos, Finch and Laplante, 1986a). Such models can be useful for describing flows in a conventional froth from a fundamental perspective. The main shortcoming associated with all of these approaches, however, is that each of them is incomplete as a froth representation. Apart from the kinetic equations, most froth models in the literature are not suitable for incorporation into a three-phase dynamic model intended for industrial applications.

1.1 General Information on Column Flotation

In order to appreciate the need for a fundamentally based dynamic model of column flotation, it is first necessary to understand the behavior of flotation columns, in general. The appearance of flotation columns was the result of a novel idea in the 1960's aimed at improving the performance of conventional flotation (Wheeler, 1966; Boutin and Wheeler, 1967). Significant gains achieved with flotation columns over conventional flotation technology include:

◊ higher grades,
◊ lower operating costs,
◊ improved operating stability,
◊ reduced maintenance requirements, and
◊ increased suitability for automatic control.

In the course of the last ten to fifteen years, the range of applications of column flotation has increased dramatically. The newer areas where column flotation is being employed include pulp and paper processing and water treatment (He et al., 1995).

Most flotation columns are characterized by a series of features, illustrated in Figure 1.1, that include:

◊ high height-to-diameter ratio,
◊ a wash water sprinkle at some point below the overflow lip,

◊ a feed addition point located at an intermediate location along the column height,
◊ a bubble generation system at the bottom of the column, and
◊ no mechanism for agitation.

However, in order to satisfy the demands of the many diverse applications, the basic column design has sometimes been altered (Jameson, 1988; Rubio, 1996).

In current research, flotation columns are normally viewed as having three distinct zones along the vertical axis. Two of the zones are separated by a visible interface resulting from the packing of bubbles at the top of the froth. The region that extends from the bottom of the column to the interface is where most of the particle collection takes place. This region is called the collection zone. Above the interface, froth stability is maintained by wash water which flows down through the films that separate the bubbles. Since gangue particles are also returned to the collection zone along with the water, this region has been termed the cleaning zone. This region may also be referred to as the stabilized froth zone since the wash water helps to inhibit coalescence and maintain froth stability. Above the wash-water-addition point, the characteristics of the froth are different. There is no continuous flow of water that replenishes the liquid draining from the films, so froth stability cannot be maintained over a large froth height. This region is generally termed the draining froth zone.

The cleaning action in a flotation column is largely determined by the wash water split. Since entrained particles are carried up by feed water reporting to the concentrate, it is very important to have a net downward liquid flow. Such flow is referred to as positive bias flow. Operating variables such as gas rate and bubble size have a profound effect on the bias and can drive it from the positive to negative direction. Besides the role of the bias water in washing down entrained particles, there is another event that promotes better selectivity and, consequently, higher grades. Such event is the dropback originated by the detachment of particles in the froth due to bubble collisions and coalescence. A circulating load is therefore established between the collection and cleaning regions.

In terms of column throughput, though, a limit is imposed by the column carrying capacity. A column carrying capacity is usually defined as the maximum rate of solids that can be transported through the froth to the concentrate. It is a function of the available bubble surface area in the froth region, which is, in turn, determined by a number of operating parameters such as gas rate and particle size. Because of the significance of carrying capacity as it relates to achievable performance, it must be considered all the way from column design through the implementation of control and optimization strategies.

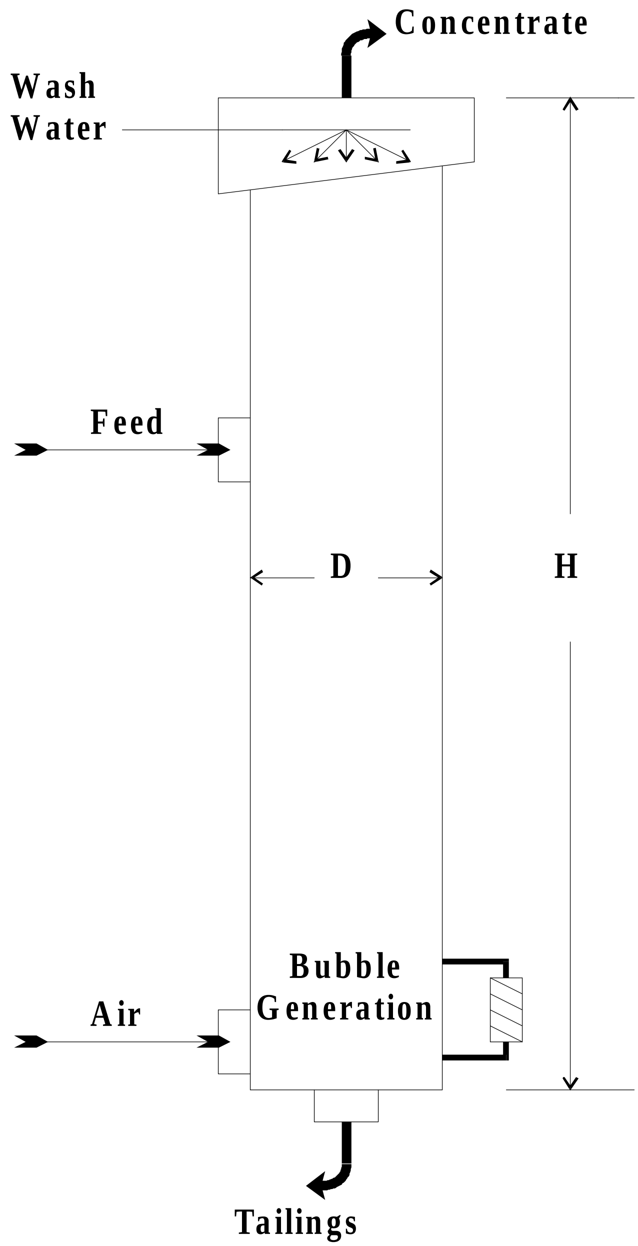

Figure 1.1: Flotation Column Layout

1.2 Objectives

The main objective of this work was to develop a fundamentally based dynamic model of the column flotation process that incorporates an accurate description of bubble-particle behavior in all three column zones (i.e., the collection zone, the stabilized froth zone and the draining froth zone). In addition to the standard equations for bubble-particle attachment, the model includes the following:

- a representation of the coalescence of bubbles in the froth zones,
- a mathematical description of the detachment of particles in the froth,
- a representation of the transition occurring at the interface,
- a representation of the extent of bubble loading and its effect on other parameters,
- a procedure to mass-balance the calculations so that at steady-state the predicted flows of material into and out of the column are equal, and
- the capability to predict countercurrent or cocurrent operation (positive-bias or negative-bias conditions).

The model also provides an estimation of the amount of material in each species that is floated and the amount of any solid species that is entrained. Additionally, it provides concentration profiles of the air and solid phases along the column axial direction, and the dynamic responses of performance variables such as grade, recovery and yield. In the development of this mathematical representation, emphasis has been placed on inclusiveness rather than simplicity.

In the course of the model development, a significant amount of time was devoted to examining different alternatives for the solution of the air-phase equations in the froth regions. Investigation of the froth also involved the design of two conductivity probes, for the estimation of air fraction profiles in both the stabilized froth and the draining froth. The experimental values were utilized to illustrate how the parameters of the froth model can be determined.

1.3 Organization

This document has been organized into 7 chapters and an appendix. Chapter 2 contains what is intended to be a very comprehensive literature review on the subject of column flotation modeling. The review includes some of the work initially applied to conventional cells that has been later modified or built upon to be applicable to flotation columns.

Extensive experimental work was performed with two types of conductivity probes to determine the change in air content in each of the froth regions resulting from bubble coalescence. The experiments in an air-water system and in an air-solids-water system are described in Chapter 3. Meanwhile, a modeling approach for representing bubble coalescence is described in Chapter 4. This approach considers the coalescence of two bubbles as a rate process. Also in this chapter, the two-phase (air-water) equations are introduced, along with the simulation results for different conditions. The model is expanded in Chapter 5 with the introduction of dynamic equations for free and attached solid species. The results of simulations carried out with the three-phase equations are also presented.

Finally, the conclusions of this project are presented in Chapter 6, while Chapter 7 contains a series of suggestions for further study derived from a review of the results of this work. An Appendix includes a listing of all the functions and programs written in MATLAB for the numerical solution of the model.