A Compartmental Model for Single- and Dual Chamber Flotation Machines

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Abstract

Since it's introduction 40 years ago, the compartmental model of flotation has become the standard approach to flotation cell modeling and simulation. However, with increasing acceptance of pneumatic and other flotation cell designs, it has become apparent that this approach breaks down for dual-chamber machines. As a result, engineers have adopted empirical correction factors to account for these observed failures of the compartmental model. Usually derived from pilot or industrial scale experiments, these factors can be costly and time consuming to determine, particularly for large greenfield concentrator projects where sample availability is limited.

This paper describes an alternative three-compartment model that can be used to model both dual-chamber and traditional single-chamber flotation machines. An application of the method is demonstrated using a pilot test program conducted at Pinto Valley's copper/molybdenum concentrator in Arizona.

Introduction

The flotation system is complex, and since the early 1990's flotation modelers have sought to overcome the complexity by compartmentalizing the flotation system into separate regimes for particle collection and froth recovery [1].

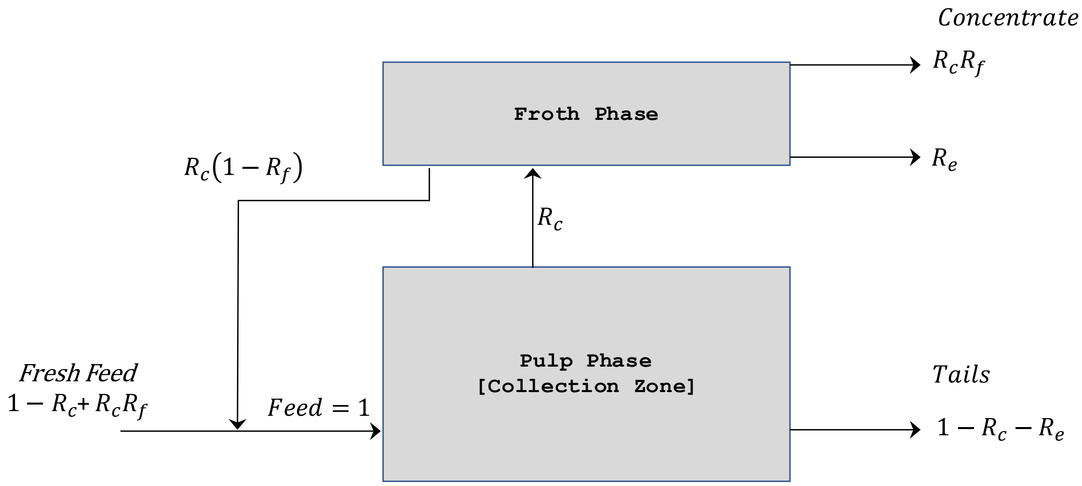

Figure 1 – Conventional 2-compartmental model of flotation systems

One of the earliest publications of so-called compartmental model appeared in 1989, in which the flotation recovery was expressed as a function of maximum theoretical recovery (R_{max}) fractional collection recovery (R_c) and froth recovery (R_f):

$$R = \frac{R_c R_f}{R_c R_f + 1 - R_c} R_{max} + R_e$$

Equation 1

Hydraulic entrainment recovery (Re) is generally accounted for through a variety of entrainment and water recovery models and applied after first determining recovery by collection (i.e. entrainment is applied to the tails). The approach has worked well for mechanical cell modelling, and over the past forty or so years, Equation 1 has been adopted by most commercial simulation platforms for the modeling and simulation of flotation processes [2] [3].

Over the past few decades, the minerals industry has increasingly accepted dual-chamber flotation cells, such as Jameson cells, SFRS and DFRS, Concorde cells, or Reflux flotation cells, as cost-effective alternatives to traditional mechanical cells. These cells illustrated in Figure 2, employ a separate mixing chamber to generate the particle-bubble adhesion, then release the 3-phase mixture into a quiescent separation chamber to disengage the loaded bubbles from the tailings. Because a large fraction of the collection recovery occurs very quickly in the mixing chamber, Equation 1 tends to underpredict the performance of these cells when using laboratory-measured rate constants. In the absence of a corrected modeling approach, most process design engineers, the authors included, resorted to using empirical correction factors applied to the rate constants.

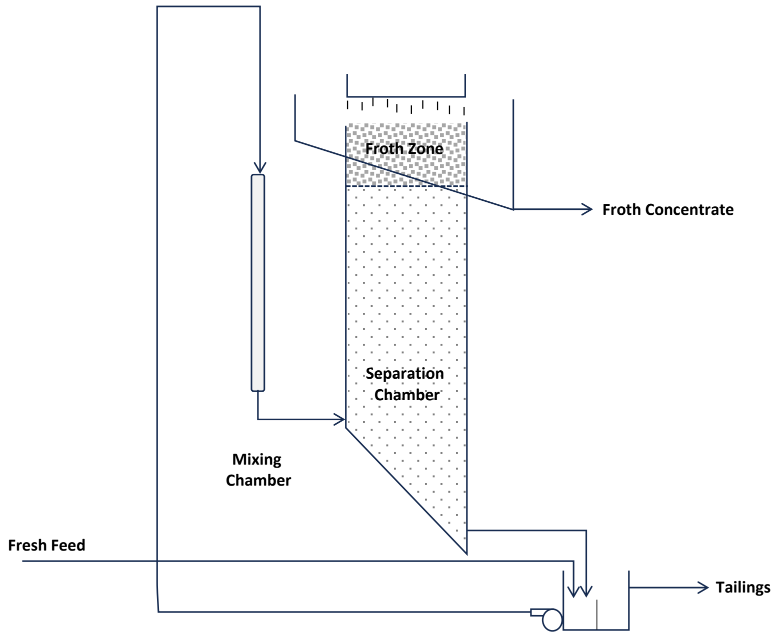

Figure 2 Schematic illustration of a dual-chamber flotation cell

In 2024, two of us (Amelunxen and Akerstrom proposed a corrected modeling approach to account for dual chamber cells. The proposed model is shown in Equation 2, where Rm is the fractional recovery by collection in the mixing chamber and Rs is the fractional recovery by collection in the separation chamber, in our case represented by the first order continuous stirred tank reactor (CSTR) model. The approach was demonstrated using a pilot plant run performed at Capstone Copper Corp's Pinto Valley mine in Arizona, United States. [4]

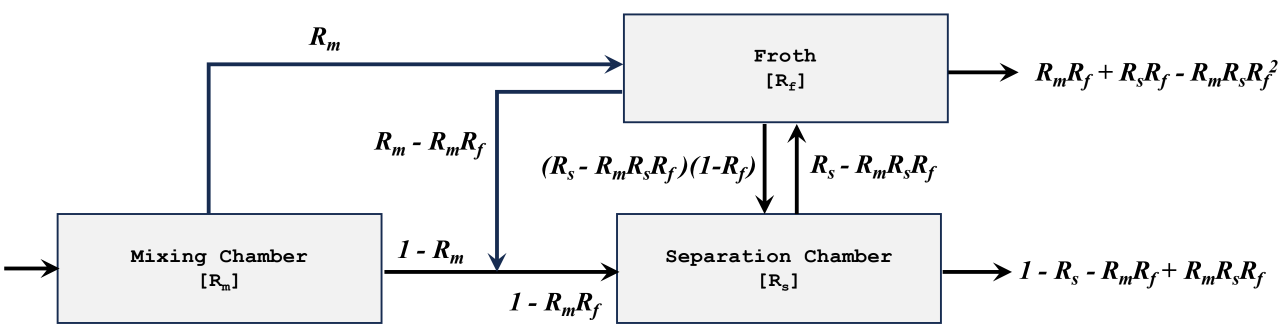

Figure 3 – 3-compartment model for dual chamber flotation machines

$$R_{flot} = \frac{R_m R_f + R_s R_f - R_m R_s R_f^2}{1 - R_s + R_s R_f + R_m R_s R_f - R_m R_s R_f^2} R_{max} + R_e$$

Equation 2

Compartmental Models for Dual Chamber Flotation Cells

While Equation 2 is a significant improvement over empirical correction factors applied to the conventional model, it still tends to oversimplify the three-compartment process occurring in dual-chamber cells because it ignores the internal recycling of material from the froth zone to the separation chamber. While this is not usually material under typical operating conditions, it can lead to model error when the froth recovery is low or when there is a high collection recovery in the separation. A better approach would be to determine the hydrophobic mineral collection in the mixing chamber, then apply Equation 1 to the new feed introduced to the separation chamber ($1 - R_m R_f$).

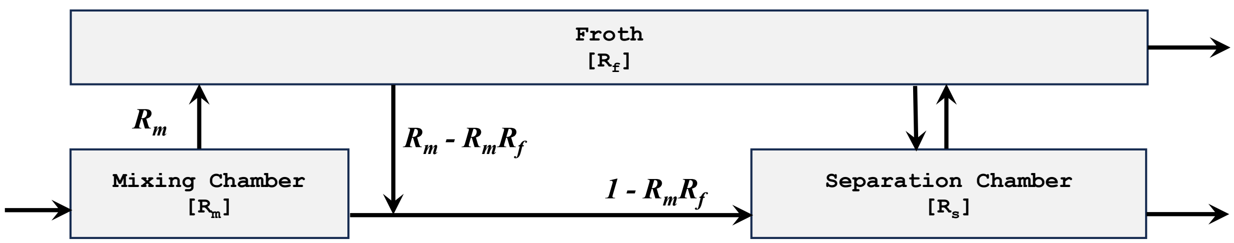

Figure 4 Alternative 3-compartment model for flotation systems

Like for Equation 2, this approach also requires one to assume that a particle collected in the mixing chamber will not detach from the bubble in the separation chamber before it reaches the froth zone. Using this approach we have:

$$R_{flot} = R_m R_f + (1 - R_m R_f)\left(\frac{R_s R_f}{1 - R_s + R_m R_f}\right)$$

Equation 3

Incorporating terms for maximum recovery and hydraulic entrainment, and simplifying, we have:

$$R_{flot} = \frac{R_m R_f + R_s R_f - R_m R_s R_f}{1 - R_s + R_s R_f} R_{max} + R_e$$

Equation 4

Some dual-chamber flotation cells operate with a fraction of the tailings recycling to the feed, mainly to maintain a constant flowrate to the mixing chamber. In these cases, the effect of the recycle is handled iteratively.

Finally, a third model was evaluated, in which the recovery in the mixing chamber is viewed as integral to the recovery in the separation chamber, i.e. the entirety of the material that is not recovered across the froth zone (the froth drainage) reports to the mixing chamber feed (Figure 5), together with the fraction of the separation chamber tailings that is required to make up the constant volumetric feed flowrate. The froth drainage recovery can be achieved through the installation of an inverted cone below the pulp/froth interface, with the cone discharge reporting to the feed pump sump, a setup similar to the Jord NovaCell™ (but without the classification equipment) and described by Jameson [5].

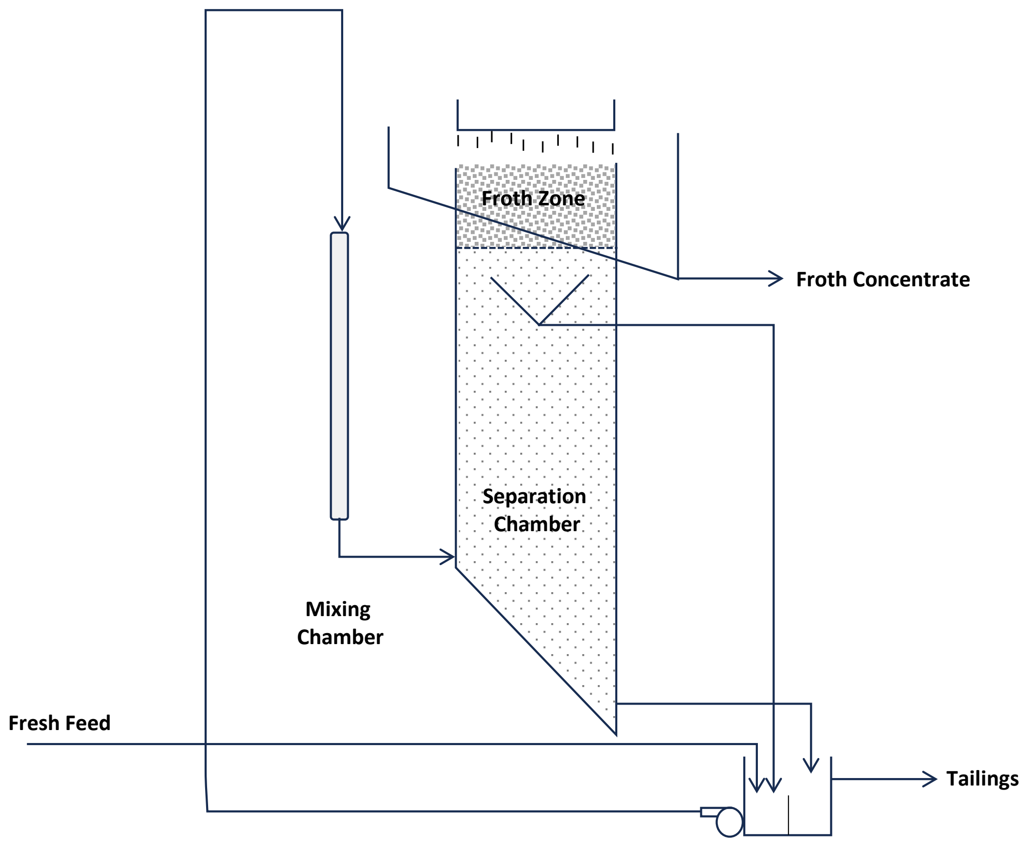

Figure 5 – Schematic illustration of a dual-chamber flotation cell with froth recycle capability

This system can be represented by Equation 1, with a minor modification to the formula for Rs. Instead of using the CSTR model to estimate Rs, we have used the CSTR model in combination with a recovery intercept at t = 0 to account for the hydrophobic particles that enter the separation chamber that are already collected due to the function of the mixing chamber (Equation 5). Figure 5 presents a graphical comparison of Equations 1, 2, 3 and 4 for a system with a collection rate constant of 1.4 min^{-1}, separation chamber residence time of 2.5 minutes, and mixing chamber recovery of 85%. As expected, this model shows a superior recovery when compared with either Equations 1, 2 or 3, suggesting that an easy way to improve the performance of pneumatic cells is to retrofit an inverted cone (and associated instrumentation and control hardware) below the pulp/froth interface. This approach could potentially be applied to conventional mechanical cells as well.

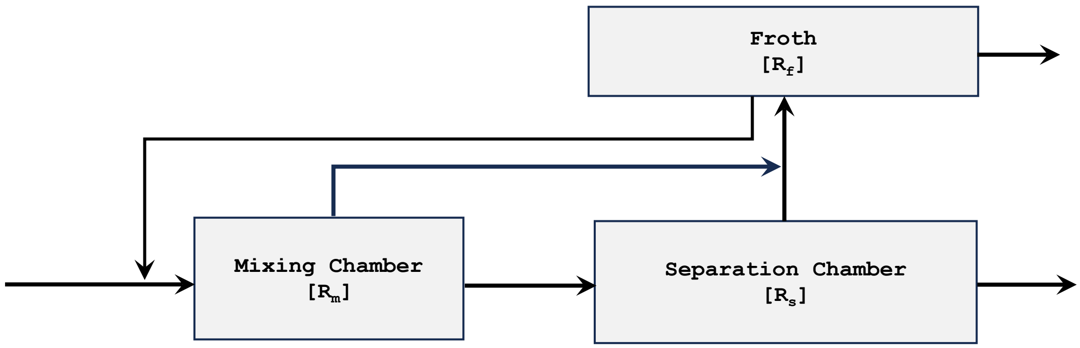

Figure 6 – compartmental model for dual chamber flotation machines with froth drainage recycle.

$$R_{total} = \frac{R_s R_f}{1 - R_s + R_s R_f} R_{max}, \quad where \ R_s = R_m + (1 - R_m)\frac{kt}{1 + kt}$$

Equation 5

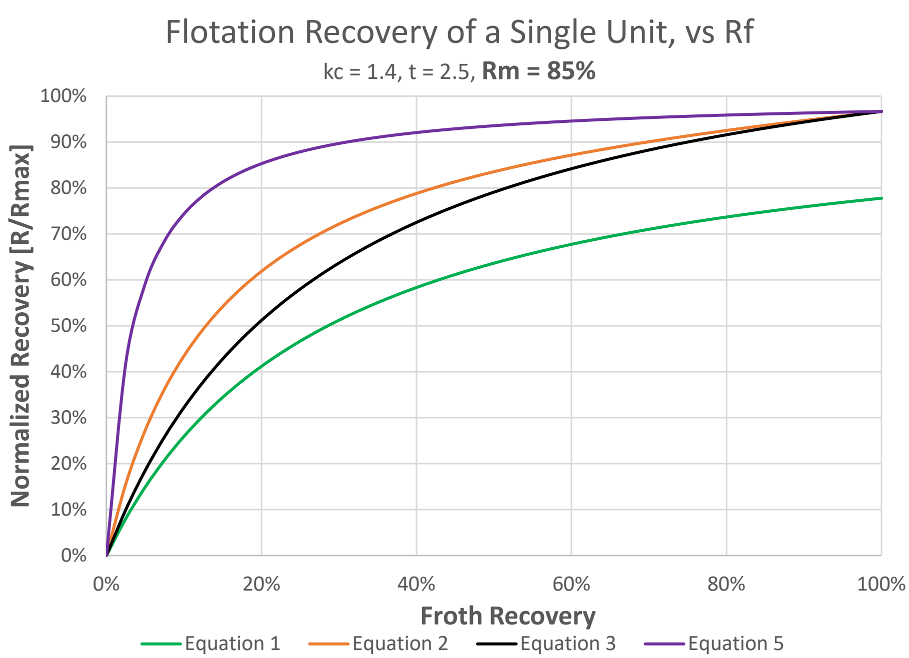

Figure 7 Comparison for four models [Eq. 1 – conventional CSTR, Eq. 2 – 2024 model, Eq. 3 – Updated model, Eq. 5 – Froth recycle model]

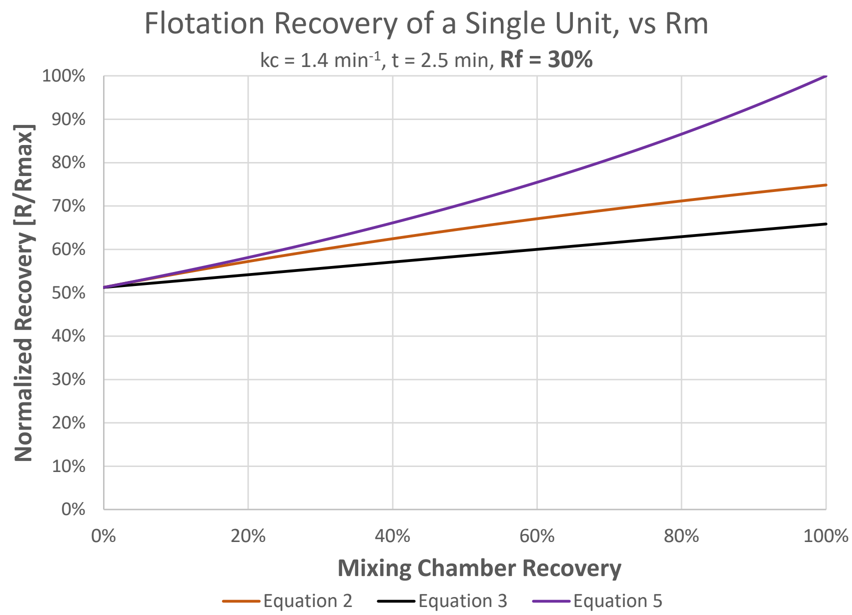

Figure 8 Comparison of four models versus mixing chamber recovery [Eq. 1 – conventional CSTR, Eq. 2 – 2024 model, Eq. 3 – Updated model, Eq. 4 – Froth recycle model]

Evaluation of Dual Chamber Flotation Machines

In 2025 a comprehensive calibration study was undertaken with a Jameson Cell pilot unit at Capstone's Pinto Valley mine. Streams tested include the Cu/Mo rougher feed, the Cu/Mo rougher tails, and various streams in the moly plant. However, at time of writing not all results are available, and therefore a comprehensive analysis will not be presented with this extended abstract. Nevertheless, results from the work available on the Cu/Mo rougher feed stream indicate that the unit achieves high recoveries in the mixing changer and froth recoveries between 20% and 55% for an ore with first order flotation rate constants of around 1.5 min-1to 2.5 min-1. For the discussion presented below, we have used the following model parameters:

- Rm = 90%
- Kc = 1.4 min-1
- Separation Chamber Residence Time, T = 2.5 min
- CSTR model for separation chamber recovery

Comparison with Conventional Mechanical Cells

Figure 9 shows the normalized cumulative recovery versus residence time in the separation chamber (or flotation cell, for mechanical cells) for various froth recoveries from 0% to 100%. It is apparent that froth recovery is critical parameter for the efficient performance of both cell designs.

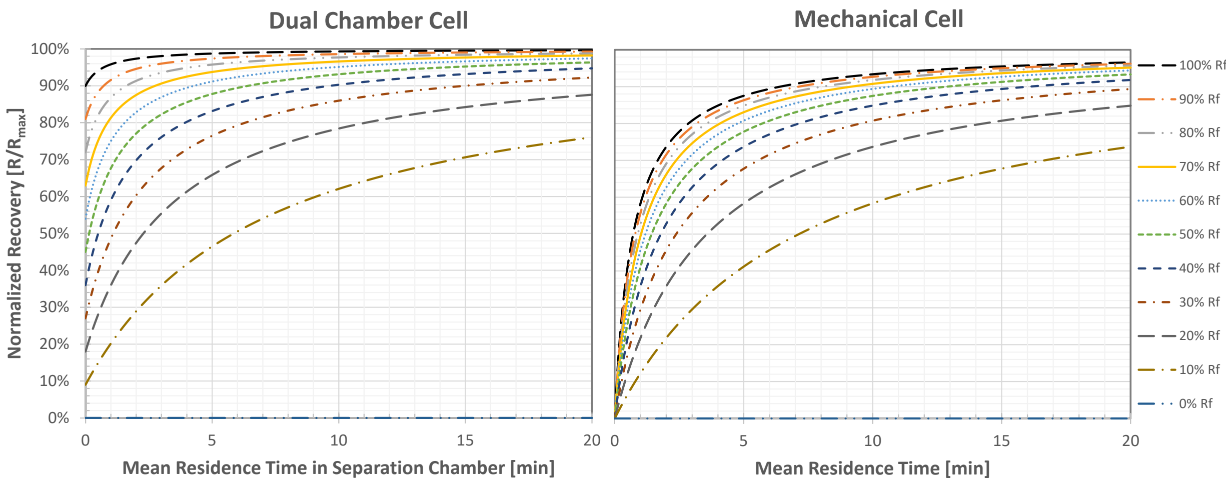

Figure 9 Impact of residence time in separation chamber for dual chamber cells (left) and mechanical cells (right)

Impact of Mixing Chamber Recovery

How important is the mixing chamber recovery, when evaluating the performance of a flotation cell? Figure 11 shows the recovery versus the Rm curves for different froth recovery, indicating that for low froth recovery there is not much of impact from mixing chamber performance. At one extreme, if the froth recovery is zero then there is no benefit from the mixing chamber. At 100% froth recovery, then the mixing chamber contributes at most 22% overall recovery points, and significantly less at lower froth recoveries. This finding is interesting, because many vendors tout the benefits of their particular mixing chamber design versus those of their peers. Assuming that a mixing chamber is broadly efficient, due to the higher gas holdup at which it is operated, then this study casts doubt on the benefits of mixing chamber design. The recovery difference of a particular design would have be extraordinary—say a difference of greater than 50% Rm—for the impact to be material at typical open launder froth recoveries. In other words, it is highly unlikely that the mixing chamber design is a significant contributor to the overall machine performance. Cell manufacturers should instead focus on operability, maintainability, and overall costs when considering mixing chamber design.

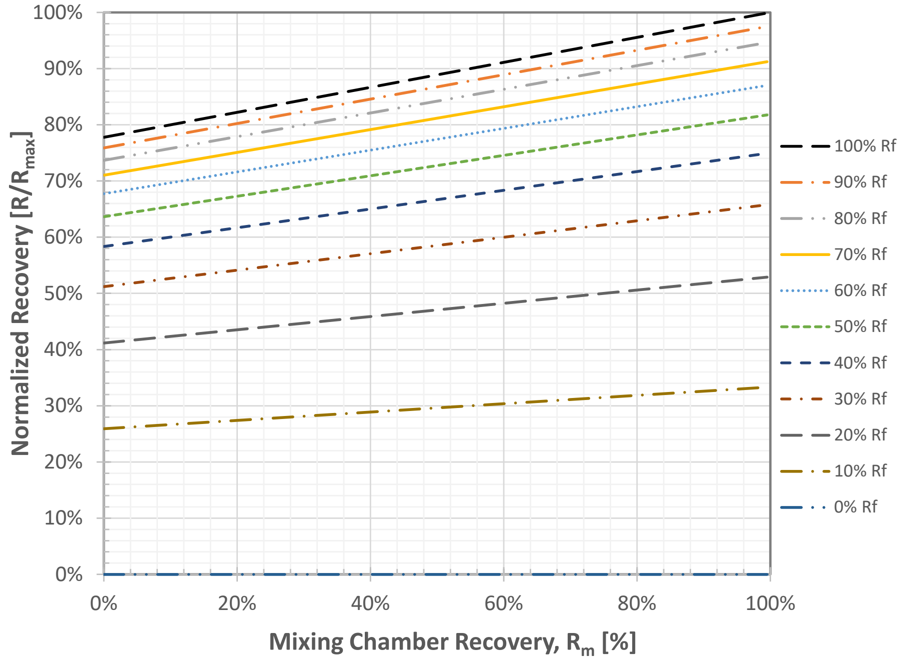

Figure 10 Mixing Chamber recovery in dual chamber flotation cells versus total recovery, 2.5 minute retention time in separation chamber

Internal Circulating Load

Many dual chamber flotation cells are designed to operate with a fraction of the tailings recirculated to the feed. This is done to maintain a constant volumetric flow rate to the mixing chamber to improve the operability and process control. Variations in the volumetric feed flow can lead to variations in the gas to pulp ratio, reducing the efficiency of the mixing chamber and leading to instability in the level control of the separation chamber. By recycling a portion of the tails, metallurgical efficiency is also improved somewhat. Figure 12 shows the overall recovery versus froth recovery for different internal circulating loads. For zero froth recovery there is not difference (because nothing is recovered) and for 100% Rf there is also little difference, because almost everything is recovered due to the efficiency of the blast tube (remember, our Rm = 0.85). For typical open launder froth recoveries of 30% to 50%, there is a 5% to 10% recovery benefit for circulating loads between 50% and 100%. Higher circulating loads require larger cell sizes, and it is unlikely that the metallurgical benefits associated with higher internal recycle rates are significant when compared to the cost of simply adding another cell. Our conclusion is that the recycle rate should be defined by inherent process variability and operability constrains, not metallurgical benefits.

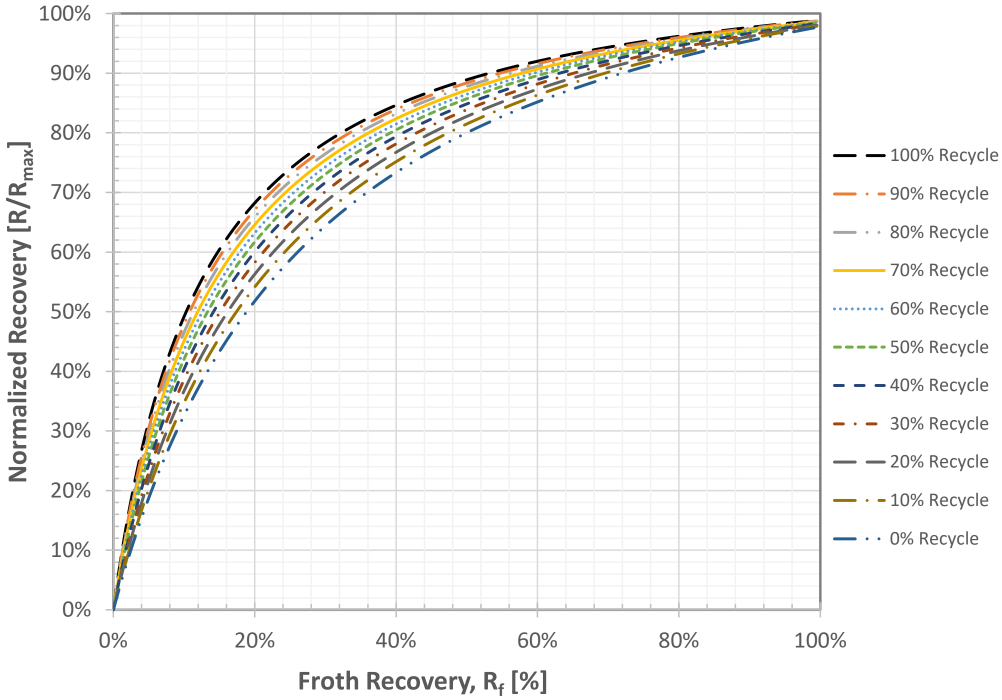

Figure 11 Froth Recovery versus normalized overall recovery for different circulating loads

Multiple Cells in Series

Figure 13 shows the cumulative recovery curve for multiple cells in series, with dual chamber cells on the left and mechanical cells on the right. Comparison of the two graphs shows that dual chamber cells requires fewer cells to achieve the same recovery, and increasing froth recovery reduces the number of either cell. For conventional circuit design, roughers flotation banks are sized by sequentially adding a flotation cell, calculating the NPV based on incremental capital and incremental recovery, and continuing to add cells until the cost of the additional cell is no longer paid back by the incremental revenue. For large tank cells operating in copper porphyry systems (our primary focus) this usually occurs somewhere around 97% or 98% of Rmax. From Figure 13, assuming 40%Rf, this would mean about 5 stages of mechanic cells or three stages of dual chamber cells. Other systems obviously may have different outcomes.

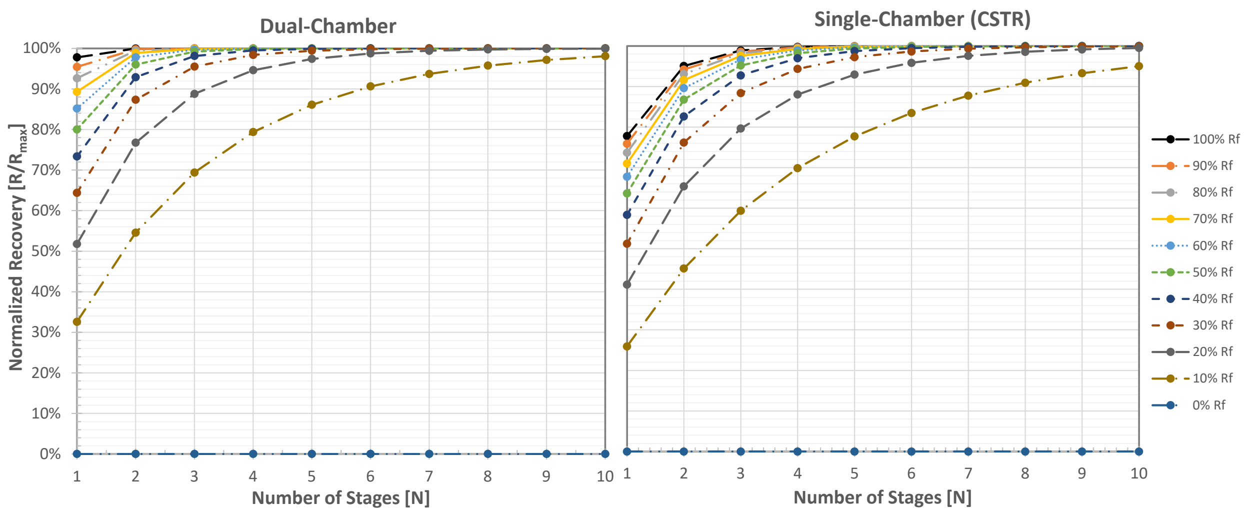

Figure 12 Impact of multiple cells in series for dual chamber cells (left) and mechanical cells (right), no internal recycle

Figure 12 was developed for open circuit cells, such as DFRs, SFRs, and mechanical cells. Figure 13 shows a similar curve but for 40% Rf and at various degrees of internal recycle.

Lastly, Figure 14 shows the same concept, but instead of recycling the tailings back to the feed, the froth drainage is captured and recycled (i.e. Equation 5). Almost 100% of the recoverable material can be collected and recovered in only two stages, assuming that 100% of the froth drainage can be captured and recycled, and that the mixing chamber recovery is 90% (as we have assumed in our models).

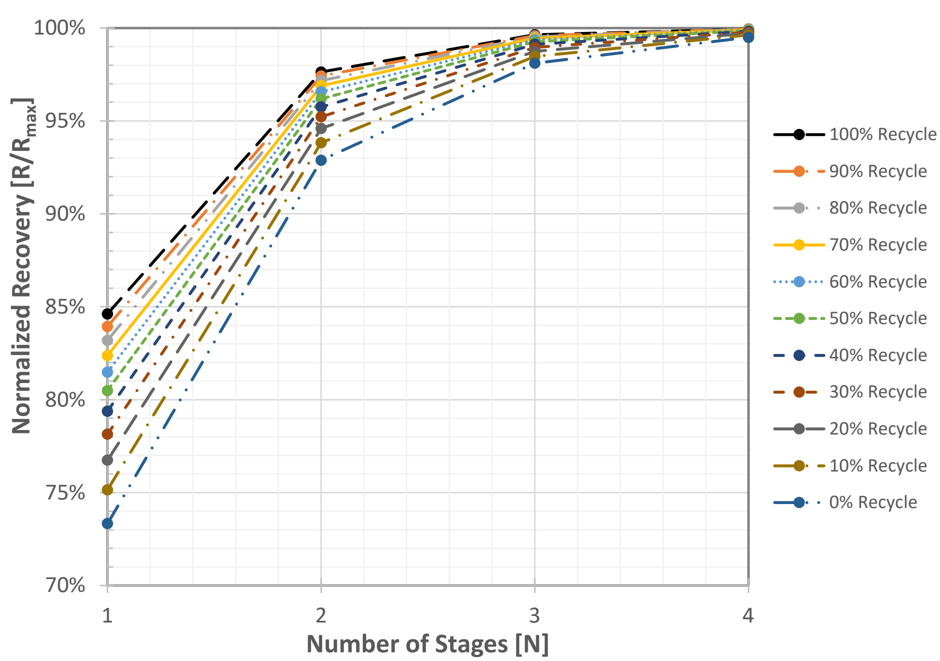

Figure 13 – Multiple cells in series with varying degrees of tailings recycle

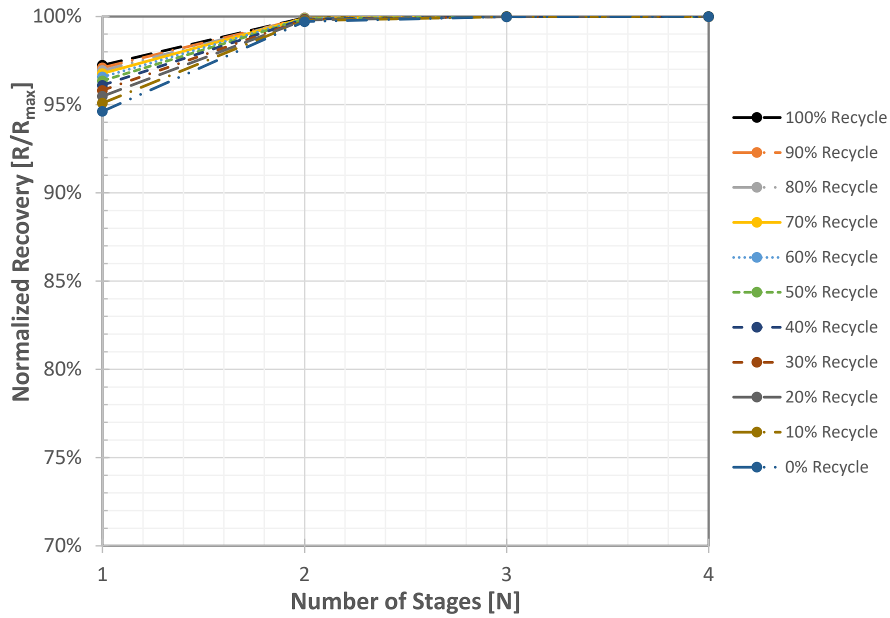

Figure 14 – Multiple dual chamber cells in series, with 100% froth drainage recycle and various degrees of tailings recycle.

Conclusions

In this paper we have proposed a new compartmental model for dual chamber flotation cells that accounts for internal recycle between the froth zone and the separation chamber.

We have also demonstrated that for most cells with the capacity for internal recycle are recycling the wrong stream. Significant metallurgical improvement could be achieved by capturing the froth drainage and returning that to the feed, rather than a fraction of the tails.

The models have shown that the design of the mixing chamber is not likely to be a significant factor in the overall cell performance. Instead, mixing chamber design should be focused on cost reduction, including ease of operation and maintainability.

Lastly, the work has confirmed that the froth recovery is the single most important contributing factor for the metallurgical efficiency of dual chamber flotation cells.

References

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