OUTOTEC FLOTATION TECHNOLOGY - AFTER THE INVENTION OF THE TANKCELL®

Sami Gronstrand[1], Christian Kujawa[2]

[1]Global Technology Manager - Flotation
Outotec Chile Ltda.
Av. Vitacura 2939 - Piso 7, Edificio Millenium, Las Condes, Santiago, 7550011, Chile
Tel: +56 2 336 2197
sami.gronstrand@outotec.com

[2]Global Flotation Support – North America
Outotec (USA) Inc.
10771 E. Easter Ave., Suite 120, Centennial, CO, 80112, USA
Tel: +1 720 873 6268
christian.kujawa@outotec.com

ABSTRACT

The TankCell® innovation by Outotec revolutionized flotation in the early nineties. It bettered good stewardship of the world's ore reserves instantaneously. However the development of flotation did not stop then. There have been significant advances in flotation since, some arguably of equal significance.

HISTORIC PERSPECTIVE

Introduction

Even though the first industrial applications of froth flotation were at the begin of the last century, and flotation was considered as a major extractive unit operation since early in the century, it has only been since the 1970s that flotation has seen advancement with research in chemistry, developments in control such as online analysis, a deeper understanding of hydrodynamics through the use of computation fluid dynamics, and most recently strides in the use of liberation analysis as a tool.

Flotation Sub-Processes

It was already in the late eighties that it was recognized by Outokumpu that flotation is essentially a two sub-process operation, and that maximization of performance meant understanding and being able to maximize performance of each of the flotation sub-processes.

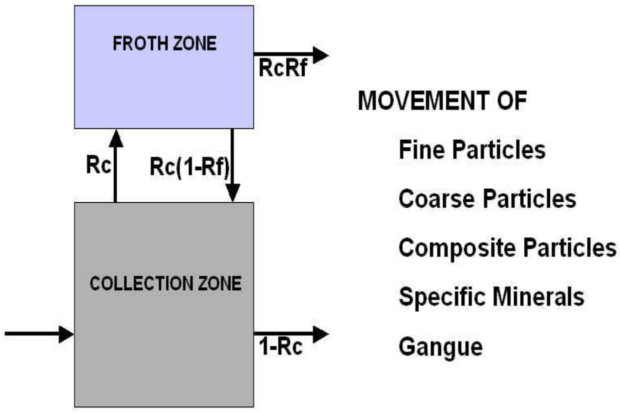


Figure 1. Depiction of the understanding of the flotation sub-processes as presented to-date in the literature, but already researched by Outokumpu in the eighties.

The flotation performance of any particular flotation machine depends its handling of the different particle classes in each of the flotation sub-processes. Although the sub-processes are separate they are nevertheless interrelated and interdependent in terms design and control when looking for optimal flotation performance.

	FEED	DESIGN	OPERATIONAL
FROTH PHASE	grade mineralogy mass pulp density particle size distribution	tank design lip length[1]	flotation gas froth depth wash water flow wash water quality froth transport distance froth surface area
PULP PHASE	grade mineralogy mass pulp density particle size distribution pulp rheology water quality	tank design mechanism design[1] rotor clearance[1]	flotation gas reagents dilution water flow dilution water quality rotor speed
1 could be changed – either in discrete steps (off-line) or with instrumentation (on-line)			

Table 1. Summary of parameters with influence on the flotation performance.

The mechanical parameters are those, which are inherent in the design and the physical supply of the mechanical flotation machines. The optimal performance is found by balancing the interdependent functions between pulp and froth phases. Generally, in order to optimize an individual cell's performance, the pulp phase and froth phase operations have to be matched. In terms of overall circuit operation however distinct overriding control strategies are required for optimization.

Size Specific Flotation

Simple review of the recovery as a function of feed particle size class shows that not all size classes behave in the same way to flotation.

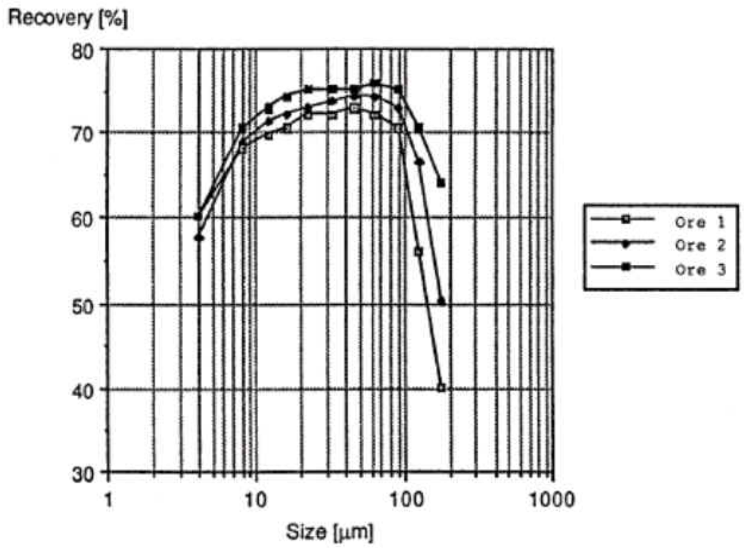


Figure 2. Recovery as a function of particle size [Heiskanen K., Kallioinen J., 1993].

The feed size distribution can be divided into three main fractions in terms of response to flotation. In the case of Figure X, which was for nickel ores, the fine fraction is less than 15micron and the coarse fraction of greater than 100micron. It should be noted that the definition of particle size class changes with equipment as well as application. In an industrial mineral application such as for example phosphate, the fine fraction might be defined as anything less than 45um and the coarse size fraction as anything larger than 425um.

The conditions required for the successful flotation recovery of these three major particle size classes differ considerably – in the pulp phase as well as in the froth phase. This is the main reason for the losses in the fine and coarse particle size classes.

	FINE	MEDIUM	COARSE
Suspension	+++	++	--
Rate of encountering	+	++	++
Probability of collision	+	++	+++
Probability of attachment	+	++	++
Total rate of aggregate formation	++	+++	+++
Probability of aggregate survival	+++	++	--
TOTAL RATE OF TRUE FLOTATION	++	+++	++
Probability of passing the froth	+++	+++	--
TOTAL FLOTATION RATE	++	+++	+

Table 2. Relative differences in typical flotation behavior of major particles size classes [Heiskanen K.; Kallioinen J.; 1994].

Research revealed that by varying the configuration of the standard Outokumpu flotation mechanism, the hydrodynamic environment could be altered in a controlled fashion to favor the fine and coarse particle size flotation to promote additional recovery in these areas of potential loss. The configuration changes at the two extremes were labeled as Multi-Mix (MM) with a focus on fine particle flotation on the one end and Free-Flow (FF) with a focus on coarse particle flotation at the other end. Both configurations are well suited at recovering the medium size particles, which normally float well and are therefore generally recovered easily.

It is important to note that it is the particle size to be floated that determines the choice of flotation mechanism configuration, and not the fresh feed size distribution.

Suspension is an independent factor and is a requirement that has to be met regardless of mechanism configuration – regardless of any design by any flotation machine supplier. Suspension can therefore be considered as a hygienic factor. If inadequate, it immediately affects the performance of the flotation machine negatively.

The recovery effort of finer or coarser particles from the pulp phase has to be matched with appropriate froth handling capabilities to ensure that the recovery action is complete. Froth handling involves looking at froth surface area availability, transportation distance as well as lip length availability. The fine particle flotation is characterized by low carrying rates but generally reasonable froth stabilities, whereas coarse particle flotation is typical with fallback, requiring short transportation distances. The design of the radial launders and the froth crowding is critical to the particle size specific flotation.

The Outokumpu Flotation Machine

Like most of the conventional mechanical flotation machines, the Outokumpu OK flotation machine was rectangular in configuration. Layout was typically with a lot of flotation machines in a row, often with several cells in one bank. Instrumentation was simple, mostly manual in nature. Limited control was possible. The largest official size was $38m^3$, though some OK50 and even one OK100 had been put into operation.

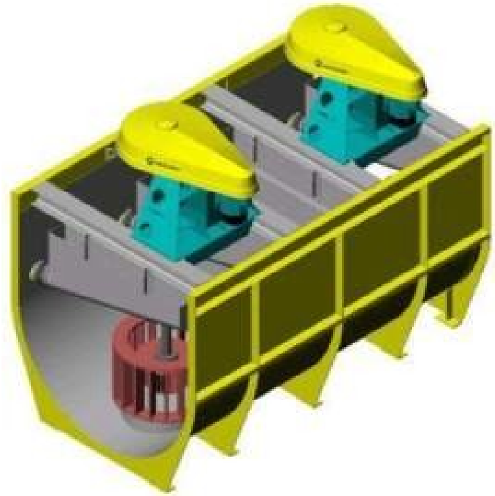
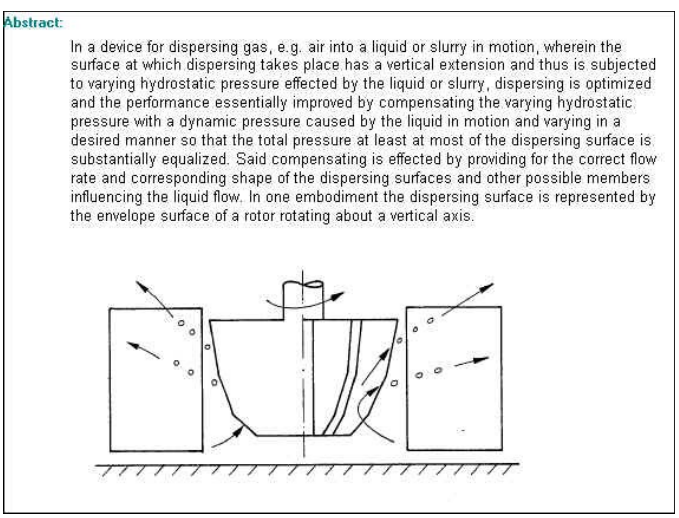


Figure 3. The Outokumpu OK flotation machine.

The Pulp Phase Sub-Process

The Outokumpu Mixing Mechanism

Kaj Fallenius invented the famous 3D Outokumpu forced air flotation mechanism, which became the hallmark of Outokumpu flotation. It offered not only all necessary suspension, but also provided unparalleled air dispersion and controllability, as required in the poly-metallic concentrators of Outokumpu.



Abstract:

In a device for dispersing gas, e.g. air into a liquid or slurry in motion, wherein the surface at which dispersing takes place has a vertical extension and thus is subjected to varying hydrostatic pressure effected by the liquid or slurry, dispersing is optimized and the performance essentially improved by compensating the varying hydrostatic pressure with a dynamic pressure caused by the liquid in motion and varying in a desired manner so that the total pressure at least at most of the dispersing surface is substantially equalized. Said compensating is effected by providing for the correct flow rate and corresponding shape of the dispersing surfaces and other possible members influencing the liquid flow. In one embodiment the dispersing surface is represented by the envelope surface of a rotor rotating about a vertical axis.

Figure 4. Excerpt from Outokumpu's patent on Kaj Fallenius's invention.

Extensive research by Outokumpu over the next quarter century was not to yield an improved design. In fact a number of competitors took to employ variants of this design in an attempt to copy the suspension and dispersion capabilities of the Outokumpu flotation mechanism.

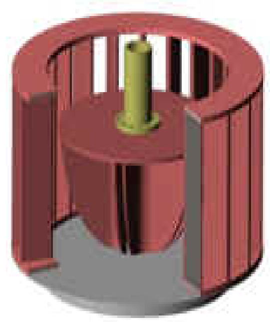
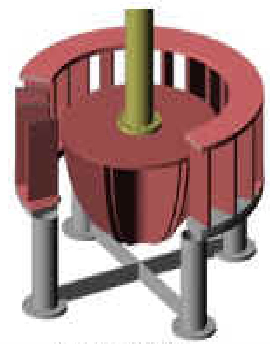
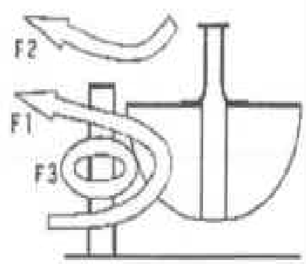
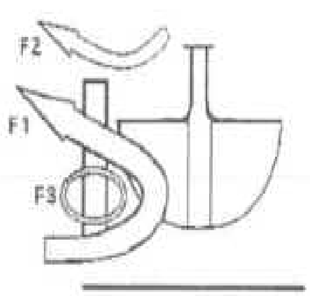
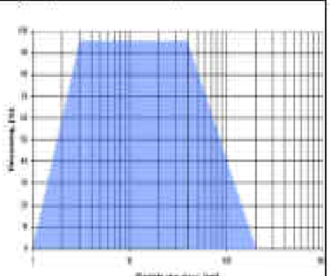
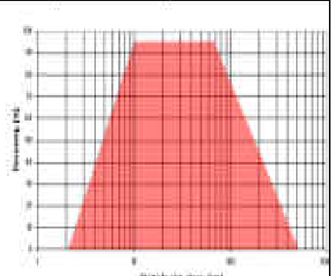
MULTI-MIX MECHANISM	FREE-FLOW MECHANISM
	
Full length stator	Half length stator
Restricted rotor clearance	Opened up rotor clearance
Higher rotor speed	Lower rotor speed
	
Lower volume main circulatory flow F1	Higher volume main circulatory flow F1
More horizontal component to F1	More vertical component to F1
More turbulent flow in F1	More laminar flow in F1
Normal volume drop back flow F2	Normal volume drop back flow F2
Higher volume internal circulatory flow F3	Lower volume internal circulatory flow F3
Higher wear rate	Lower wear rate
Higher power consumption	Lower power consumption
	
EXAMPLE PERFORMANCE RANGE	EXAMPLE PERFORMANCE RANGE

Table 3. Configuration settings and effects of the Outokumpu flotation mechanism.

The Froth Phase Sub-Process

Froth Crowding

The exploitation of lower grade ores and the increase in flotation machine size revealed that at times froths of low mineralization, especially in scavenger applications, exhibited very low froth volumes. With shallow froth depths, the froth had to move over larger distances to the launder. Here too, research in Outokumpu revealed already in the eighties the benefit of Froth Crowding.

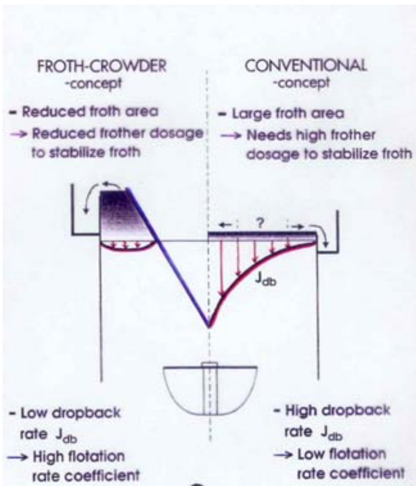


Figure 5. Froth Crowding contrasted to the froth handling achieved without.

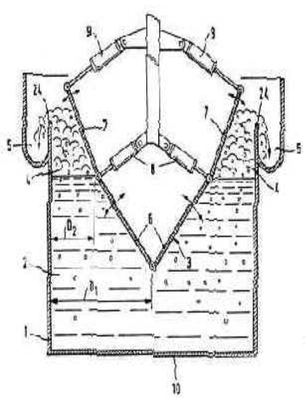


Figure 6. Froth Crowding invention by Timo Niitti and Joukko Kallioinen.

Additional Launder Capacity

During the conventional flotation era, an alternative to Froth Crowding proved to be the use of additional launders in the top of the flotation machine. Various configurations were adopted. In some cases transverse launders were added. Outokumpu pioneered the use of hanging launders, which were suspended from the top of the flotation machines, off the bridge. Shown in Figure X. A bottom and pipe-through-wall discharge was used for the concentrate removal. The hanging launders provided additional lip length, natural Froth Crowding as well as reduced froth transportation distances.

THE TANKCELL®

Whilst the use of the cylindrical tank in flotation was not new to flotation (the Maxwell cell in Canada, columns in general, the Serrano cell in Peru), it was the synergistic effect of a number of independent innovations coming powerfully together, which brought about the step change of flotation technology, setting a new standard.

The use of the cylindrical tank allowed the perfect marriage of round mixing mechanism, in this case the best mixing and air dispersion instrument available, to a cylindrical tank, eliminating stagnant zones, dead areas as well as imperfect flow patterns in the pulp phase.

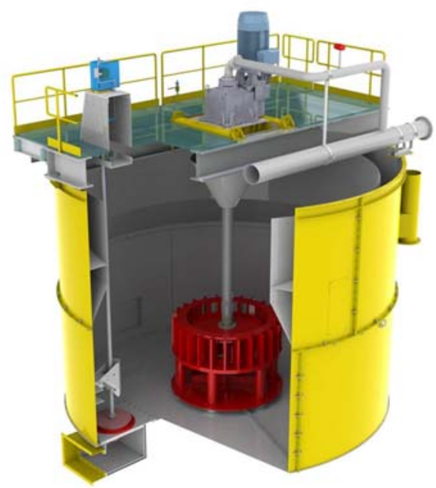


Figure 7. State-of-the-art Outotec TankCell®.

The simplified unison radial flow pattern in the pulp lends itself to the use of computation fluid dynamics. Gaining more understanding and control of the flow patterns within the flotation machine, allowed the design of larger and larger mixing mechanisms and therefore also flotation machines with confidence. It also allowed a finer matching of the rotor/stator contribution within the tank, important pre-requisite to scale-up. Computational fluid dynamics modeling suddenly became feasible.

The 3D nature of the heritage Outokumpu mixing mechanism, the fact that it is bottom stirred and the fact that the Outotec machines by nature were forced air flotation machines, were the fundamentals necessary to provide an easy path to scale-up.

The controlled flow patterns achieved with the cylindrical design facilitated the proper matching of pulp phase design and froth phase design, thereby optimizing the overall cell performance potential.

The development led to the unit flotation reactor concept, with capabilities to provide:

- Mechanical design specific for performance in specific applications
- Operational capability specific for performance in specific applications

The gained understanding resulted in the design of larger flotation machines. Flotation applications could be equipped with larger and fewer units. Individual stepping of the cells was found to be most beneficial. The larger sizes and reduction in number of flotation machines promoted investment into increased instrumentation.

TECHNOLOGY DEVELOPMENT SINCE THE ADVENT OF THE TANKCELL®

The Pulp Phase Sub-Process

The FloatForce® Rotor and Stator – The Flotation Mechanism

The heart of the mechanical flotation cell is the rotor-stator mechanism, which mixes the content, disperses air and generates kinetic turbulent energy. This turbulence is needed to accelerate the particles and give sufficient energy to the particle to attach to the bubble. Thanks to recent advances in hydrodynamic understanding and the use of computation fluid dynamics, Outotec has been able to develop and release a new flotation mechanism, called FloatForce The mechanism is available for new installations as well as for existing OK and TankCell® equipment as a simply installed spare part. The FloatForce mixing mechanism incorporates all the good features of the renowned OK-mechanism combined with new ideas, with the result of increased performance in several areas [Grönstrand et al., 2006]. Operators of pumps and flotation cells know well that air deteriorates the performance of impellers. Air occupies more or less the space that should be filled with slurry and in worst case the pumping stops completely. In all flotation cell mechanisms (independently how air is introduced) used today the air is introduced into the central area of the rotor and therefore the mixing efficiency is decreasing strongly with increasing amounts of air.
In the FloatForce rotor, the air is introduced to the peripheral area of the impeller and thus the core of the rotor is used only for slurry pumping without disturbing it with air.

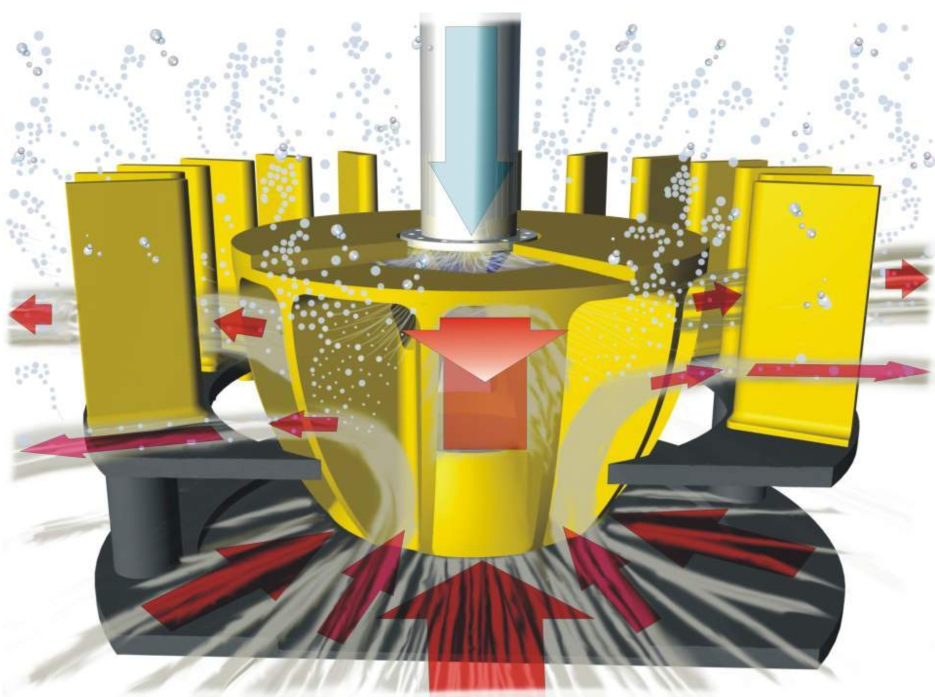


Figure 8. Artist's cutaway impression of the FloatForce® flotation mechanism in operation.

Therefore the mixing capacity remains high even when a high air feed rate is used. Because the slurry flow through the impeller remains high, it is possible to disperse large amounts of air evenly into the pulp. High pulp flow also guarantees low or no sanding at the cell bottom.

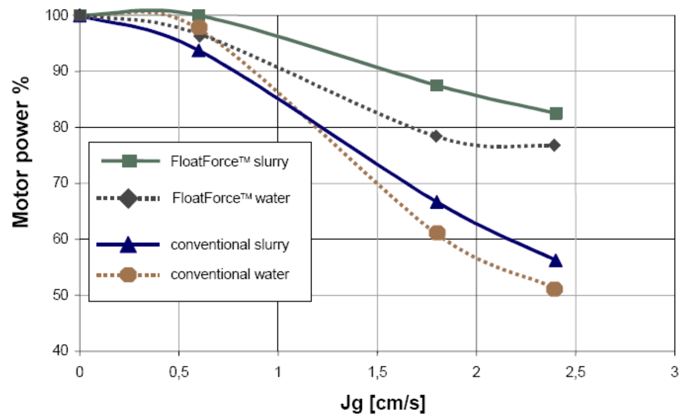


Figure 9. Power curves of Conventional OK (Multi-Mix) and FloatForce® at different air feed rates.

The flat power curve of the FloatForce presents a new kind of toolkit for the operator.

The increased mixing changes the flow profile inside the tank, carrying more coarse particles higher up in the cell, as can be seen in the figures below.

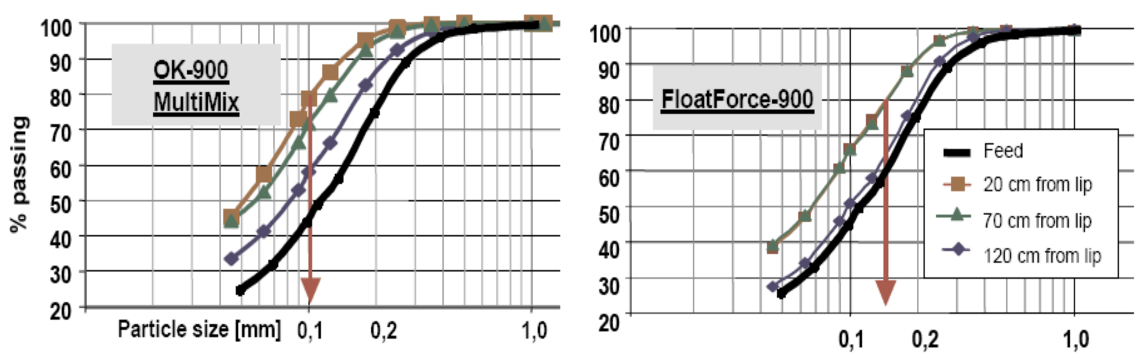


Figure 10. Particle size distributions at various depths in the OK-38 scavenger cell. LHS: OK Multi-Mix, RHS: FloatForce®.

It is clear that coarser concentrates can be produced with the FloatForce. Another example of this is the coarse apatite scavenger flotation at Yara's Siilinjärvi concentrator plant. Thanks to improved mixing the recoveries are higher and concentrate is coarser. A comparison with uniform feed fed into parallel OK-38 cells is shown in the table below.

Test	Mechanism	Concentrate %	Recovery %	Concentrate % +250µ
1	**FloatForce®**	**6,39**	**54,1**	**27,1**
	Conventional	7,03	43,6	24,9
2	**FloatForce®**	**5,36**	**46,5**	**28,9**
	Conventional	4,82	40,5	24,4

Table 4. A plant survey with 900 mm mechanisms in a coarse particle scavenger flotation application.

FloatForce stator is open in the inlet area and thus the slurry flow into the rotor is free. The blades are individually bolted onto a supporting frame, which makes maintenance of the flotation cell significantly safer and easier. Only relatively lightweight blades are individually changed. By using different stator blades it is simple to test and find optimal wear resistant material for each application. CFD was used to optimize the flow characteristics in critical areas of the mechanism, and the result is longer lasting wear parts.

Key Feature	**Effect**	**Potential result**
Increased mixing at the same aeration rate	Increases bubble-particle collisions	→ Higher recovery
	Increases the suspension of coarse solids	→ Higher coarse recover → Coarser grind size (if liberation allows)
	Enables the use of higher slurry density	→ Added solids retention time → More throughput
	Pumps more slurry	→ Less sanding
Maintained mixing at a *higher dispersed aeration* rate	Increases bubble surface area flux S_b	→ Higher recovery
Maintained mixing *and* aeration rate (selection of speed when specifying equipment)	Reduces power draw in no air / startup situation	→ Reduced energy costs → Reduced capital expense (motor & cabling) → Lower spare part cost
Individual lightweight stator wear parts	Enables easier and safer stator maintenance	→ Faster maintenance → Less time spent in confined space
	Enables testing of various wear materials	→ Longer wear lives → More availability
	Enables changing of individual stator blades in case of impact of foreign objects	→ Reduced wear part costs

Table 5. Response Summary with the Use of the FloatForce® [Gronstrand S., Bourke B.; 2008].

FlowBooster™ for Increased Laminar Mixing
The new FlowBooster is a patented additional impeller bolted onto the lower shaft of the standard mixing mechanism. The pitch blade turbine is attached to the lower shaft above the normal flotation mechanism in the bottom of the cell.

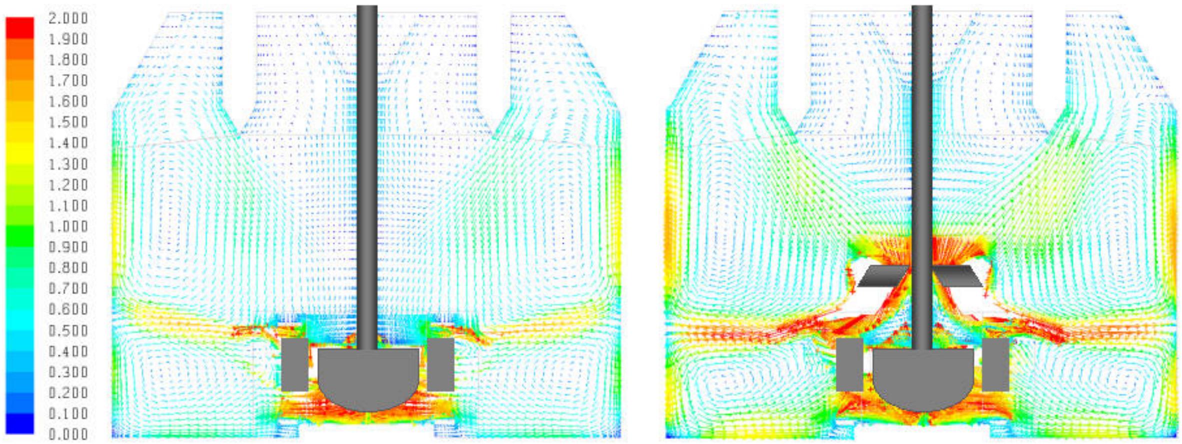


Figure 11. Flow velocities in a cell with a center (donut) launder arrangement. LHS: Without FlowBooster™; RHS: With FlowBooster™.

CFD work has shown a 7% improvement in the secondary downward-pushing flow and a 10% improvement in the primary radial mixing flow. In practice a 10% increase in power consumption at the same rotor speed is seen.

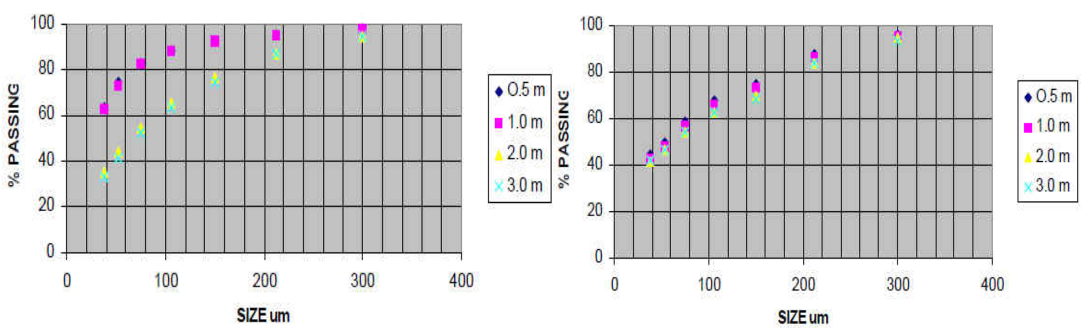


Figure 12. Mixing Enhancement of the FlowBooster™ [Peter Bourke, 2009]. LHS: Without FlowBooster™; RHS: With FlowBooster™.

The increase in mixing flow shows in the solids distribution throughout the flotation machine.

Figure 13. Reversible FlowBooster™ installed in TankCell®300 flotation machines at Macraes in New Zealand.

Figure 13 shows how the FlowBooster is easily installed by bolting onto the lower shaft, which is why it can also be easily added to existing flotation machines. The internal components, which allow the unit to flip over when the direction of the drive mechanism is changed, are completely sealed and greased for life. This is important, as the drive mechanism direction should be changed on a regular basis, which virtually doubles the life of the mixing mechanism components through bi-directional wear.

The additional pumping reduces the pumping load component of the flotation mixing mechanism duty, which translates to enhanced air dispersion capability and shear intensity output. The mechanism can therefore be slowed down for equal metallurgical performance, however incurring significant power saving in the doing. This was demonstrated with the TankCell®300 comparative test work in Chuquicamata [Yanez et al., 2009], where step change metallurgical performance was achieved at 0.58kW/m^3 specific energy consumption inclusive of blower.

	2xTankCell®160 OK-FreeFlow (installed 2001)	**1xTankCell®300** FloatForce®	**1xTankCell®300** FloatForce® +FlowBooster™ -10% speed
Copper Recovery	~ 52 %	+ 3,7 % units	+ 5,3 % units
Copper Grade	~19 % Cu	+1,0 % units	+1,1 % units
Specific Energy (Mechanism + Blower)	0,71 kW / m^3	0,66 kW / m^3	0,58 kW / m^3
Energy		- 7 %	- 18 %

Table 6. Comparative Flotation Results from Chuquicamata [Yanez et al., 2009].

The FlowBooster has also the potential for optimization of reagent addition to large flotation machines. Reagents are added with a tube immediately above the FlowBooster, which in turn forces the reagent down, to be perfectly mixed by the main mechanism.

The performance characteristic of the FlowBooster is however more important for the flotation of coarse composite (semi-liberated) particles. Partially hydrophobic coarse particles have an extremely weak connection to the bubble. Excessive turbulence in the pulp phase and at the pulp/froth interface should be therefore be minimized. The downward-pushing motion of the FlowBooster enhances the circulation of the top part of the tank in a very quiescent, laminar manner aiding the upward flow of collected material exiting the rotor-stator, while not affecting the top froth collection layer of the cell.

The Froth Phase Sub-Process

Introduction

The advent of the TankCell® allowed the marriage of a cylindrical Froth Crowding device into a cylindrical tank, here too eliminating stagnant zones, dead areas and imperfect flow patterns in the froth phase.

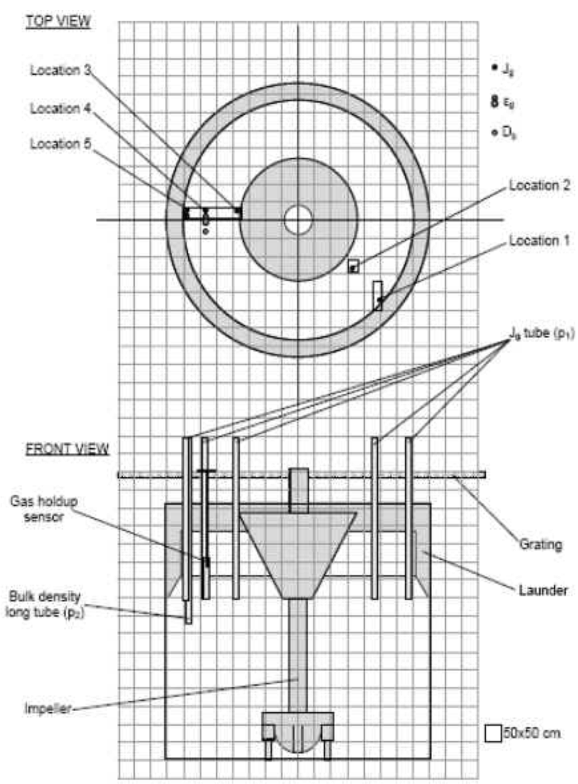


Figure 14. Sensor array setup for flotation air measurement on the Chuquicamata TankCell®300 flotation machine [Yanez et al., 2009].

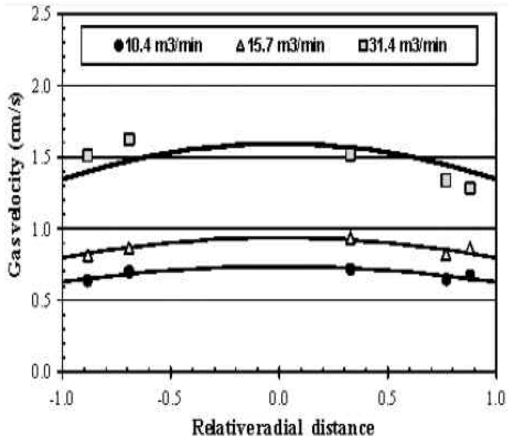


Figure 15. Pulp phase radial superficial gas flow rate profiles measured in the Chuquicamata TankCell®300 flotation machine [Yanez et al., 2009].

As in the pulp phase the unison radial flow patterns allow exercise of control to the froth phase. The continuously expansion of the froth moving outward lends further impetus to the movement of the froth.

Flotation air measurements on the Chuquicamata TankCell®300 demonstrated again the flat air distribution profile and the radial nature of the flow patterns within the pulp phase.

It is this unison and flat radial air distribution profile, shown in Figure X, which makes the Froth Crowder and the new radial launder designs so effective.

Radial Launders

Whereas launder extensions used on the conventional cells yielded mixed results, primarily because of uncontrollable flow patterns in the pulp below the froth phase and therefore uneven superficial gas rates across the froth surface, this was not the case with the cylindrical TankCell®. Initial designs employing deep launders showed interference with some surface pulp flows.

This led to the deep launders being replaced by a new shallow design, which consumes little pulp volume. Simultaneously the radial launder was integrated with the adjustable concentrate lip, which means that the concentrate lip and radial launders are leveled at the same time, a procedure required only during initial commissioning.

A pie-shape design minimizes froth transportation distances, while at the same time adding significant lip length to the flotation machine.

The radial launder design has enabled increased froth removal, significantly improving the recovery over the froth phase, making it possible to handle the large concentrate tonnages which need to be recovered by the new large flotation machines.

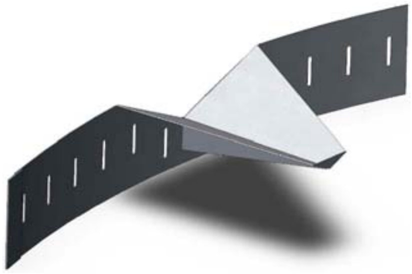


Figure 16. Integrated launder and adjustable concentrate lip segment.

Figure 17. Top view of radial launder arrangement in a TankCell®.

Advanced Froth Depth Control

It is well known that separate slurry level PID controllers operating in a sequence of tanks can sometimes perform unsatisfactorily, since the tanks are interconnected. Control action in one cell causes disturbances down- and up-stream. This problem has been solved with a solution called EXACT-level control. This concept is based on advanced feed forward control and continuous adaptive tuning. It simultaneously monitors the whole flotation line and the other sources of disturbance such as upstream control valves and pumps, and effectively compensates the disturbances before they affect the froth levels in the cells.

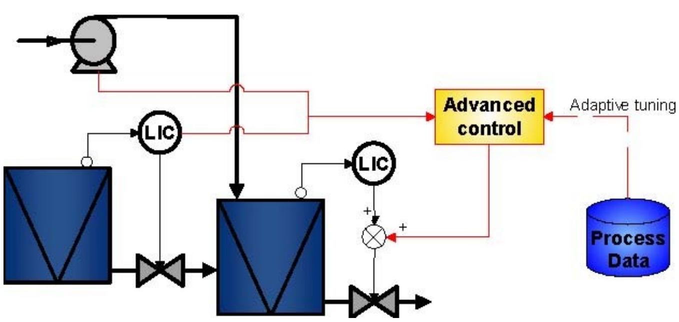


Figure 18. Principle of operation of the EXACT-level control solution.

Froth Image Control

Froth imaging and cameras have been available for a little less than 10 years now. Typical froth characteristics measured are froth speed, bubble size and bubble stability. In the most basic application the confirmation of froth movement is an indication that the flotation machine is online and producing. Such information is most useful at management level. The implementation of froth imaging presupposes that proper and independent froth depth and flotation air control exists. A workable control strategy must be designed, implemented and tuned in order to utilize the measurements in a productive way. This calls for expert system functions along the lines of "a DCS controller was developed to emulate exactly what the process technician does but more consistently and more frequently" [Brown et al., 2000].

Froth imaging coupled with higher level balancing and optimizing controls provided the plant in question an increase in copper and gold recovery of 2,4 and 5,6 % respectively [Brown et al., 2000].

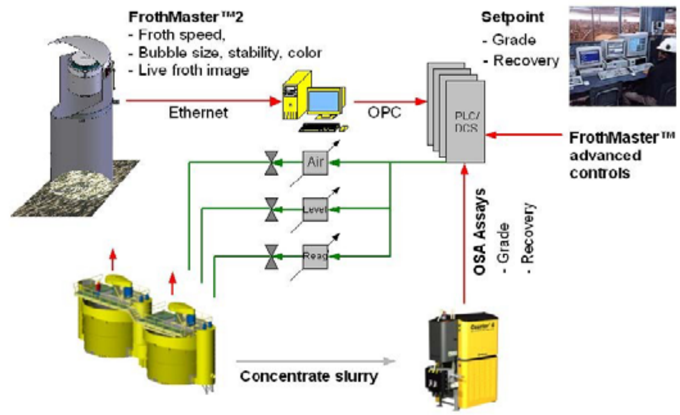


Figure 19. FrothMaster™ control concept.

The use of increasingly larger flotation machines requires instrumentation and control. The large tonnage of mined ore inventories demand that active control be imposed.

When the cell is designed to be responsive to changes in the operating parameters, it also lends itself to efficient high-level expert control systems. For example, concentrate grade control using the FrothMaster™ froth imaging system is only possible if the set points in air, level and reagent addition are yielding a logical response. When designers of the Flotation Cell and the Intelligent Instruments and Automation Systems sit in the same room, it is possible to implement this holistic approach.

CONCLUSION

The cylindrical TankCell® concept constituted a technology step change at the time of its inception. It was this innovation and the correct existing platform of bottom stirred, forced air flotation machines equipped with heritage Outokumpu mixing mechanism, which provided the smooth transition to ever larger flotation machines.

Now however, with developments such as the FloatForce® flotation mechanism, the FlowBooster™, mature froth handling technology and modern flotation control instrumentation, flotation has undergone a complete transformation. It appears that flotation technology has entered a new era – perhaps the golden age of flotation.

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