

SIGNIFICANCE OF EXPOSED GRAIN SURFACE AREA IN COARSE PARTICLE FLOTATION OF LOW-GRADE GOLD ORE WITH THE HYDROFLOAT™ TECHNOLOGY

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ABSTRACT

Conventional flotation machines are typically limited to a particle topsize of 150-200 microns due to inherent constraints created by the pulp and froth phases. To overcome these limitations, a novel fluidized-bed flotation system called the HydroFloat™ Separator has been developed specifically for the purpose of floating coarse particles containing only small amounts of exposed hydrophobic minerals. Over the last decade, this technology has been successfully applied to industrial minerals with several full-scale units installed to recover particles up to and exceeding 3,000 µm diameter. More recently, sulfide-based test work has shown that this novel device is also capable of recovering metalliferous values at a grind size that is much coarser than currently used in industrial concentrators. In the current study, high resolution X-ray microtomography (HRXMT) was used to experimentally compare the degree of exposed grain surface area necessary to recover coarse particles using the HydroFloat™ technology to that attainable using a traditional mechanical flotation cell. The data indicate that exposed grain surface area is a critical factor for coarse particle flotation. For the gold-bearing sulfide ore examined in this study, the HRXMT data suggest that near complete recoveries of coarse (850x500 µm) multiphase particles containing as little as 1% exposed grain surface area were realistically attainable using the HydroFloat™ technology. As such, this new technology may offer a unique opportunity for increasing concentrator capacity by increasing the primary grind size needed for rougher/scavenger separations.

KEYWORDS

Coarse particle flotation, X-ray computed tomography, exposed surface area, HydroFloat™

INTRODUCTION

On 30 July 2002, Eriez Manufacturing was awarded a U.S. patent for the world's first air-assisted density separator specifically designed for the selective separation of coarse hydrophobic particles that were too large to be recovered by traditional froth flotation equipment (U.S. Patent No. 6,425,485, July 30, 2002). The technology, which is now marketed under the tradename HydroFloat™, uses an aerated fluidized bed of solids to create particle-bubble aggregates that can be separated based on differences in buoyancy. The effectiveness of the HydroFloat™ for coarse particle flotation has been demonstrated industrially with more than 50 units installed worldwide. However, to date, all of the installations of this technology have been placed into service within industrial mineral applications such as coal, potash and phosphate. Based on these successes, the technology is now being demonstrated for the flotation of coarse poorly-liberated sulfide particles. If high recoveries can be achieved at a coarse particle size, numerous opportunities exist for significant cost savings and capacity enhancements in sulfide comminution circuits. For example, based on Bond's grindability law, an increase in D80 grind size from 150 to 300 µm could potentially increase grinding mill capacity by more than 50% for a typical base metal concentrator. In addition, it is expected that substantial improvements in water recovery and recycle may be possible using this new technology. In this paper, experimental test results are presented that compare the size-by-size separation performance of the HydroFloat™ and conventional flotation processes for the upgrading of a low-grade gold-bearing sulfide ore. Froth and tailing products from these two flotation technologies were then examined by high resolution X-ray microtomography (HRXMT) to determine whether the HydroFloat™ separator would be capable of recovering particles with a lower exposed grain surface area.

HYDROFLOAT™ SEPARATOR

Practitioners working in the sulfide mineral industry have long recognized the particle size limitations associated with traditional froth flotation processes. For example, Figure 1 shows the size-by-size recoveries obtained for ore samples of chalcopyrite and sphalerite upgraded using a conventional laboratory flotation machine. In both cases, a sharp decline in mineral recovery is noted for particle diameters larger than approximately 100 microns, a cutoff which is largely independent of reagent addition. Reasons cited in the technical literature for the decline in coarse particle recovery include particle detachment and inadequate buoyancy of particle-bubble aggregates (Jameson, Nguyen, & Seher, 2007). Further, the cutoff is expected to be related to liberation, or more specifically, to the exposed grain surface area. However, theoretical and experimental studies conducted by researchers working in the Eriez Flotation Division indicate that these inherent limitations can be overcome through the development of a fluidized-bed flotation machine specifically designed for the selective recovery of feeds containing very coarse particles. This innovative technology, which is sold commercially under the tradename HydroFloat™, utilizes an aerated fluidized bed of solids to effectively prevent the loss of coarse hydrophobic particles (Kohmuench, Mankosa, Kennedy, Yasalonis, Taylor, & Luttrell, 2007). According to Kohmuench, Mankosa, Yan, Wyslouzil, and Christodoulou (2010), and Kohmuench, Thanasekaran and Seaman (2013) the HydroFloat™ separator offers several key advantages for treating coarser feed streams including reduced turbulence, improved bubble-particle collision and attachment, elimination of buoyancy restrictions, increased particle residence time, and plug-flow separating conditions.

A simplified schematic of the HydroFloat™ separator is provided in Figure 2. As shown, the device consists of a circular tank subdivided into an upper freeboard compartment, a middle separation chamber and a lower dewatering cone. Similar to a typical hindered-bed separator, feed solids are introduced just above the middle separation chamber and are permitted to settle against an upward rising current of water or other fluidizing medium. The upward flow creates a fluidized "teeter bed" of suspended particles with high interstitial liquid velocities that resist the penetration of slow settling particles. Gas is then introduced and dispersed along with frother into the fluidization network through an externally located high-shear sparger system. As the air bubbles rise through the teeter bed, they become attached to hydrophobic particles, thereby reducing their effective density. The particles may be naturally hydrophobic or made hydrophobic through the addition of flotation collectors. The lighter bubble-particle aggregates rise to the top of the denser teeter bed where they accumulate due to their lower density. Particles having

even minimal exposures of hydrophobic surfaces and bubble attachments are very effectively prevented from being lost to tailings by the action of the teeter-bed. The accumulated aggregates lift off the teeter bed interface and are carried upward through the freeboard compartment due to increased buoyancy created by subsequent bubble attachments. The bubble-particle aggregates are then rapidly carried by the rising flow of fluidization water upward through the freeboard compartment where they overflow into a collection launder. Due to the constant overflow of fluidization water, only a thin froth layer forms at the top of the flotation pulp. Hydrophilic particles that do not attach to the air bubbles (i.e., rock) continue to move down through the teeter bed and eventually settle into the dewatering cone and are discharged through the underflow nozzle. The flow through the underflow nozzle is automatically controlled based on readings from an electronic pressure transmitter.

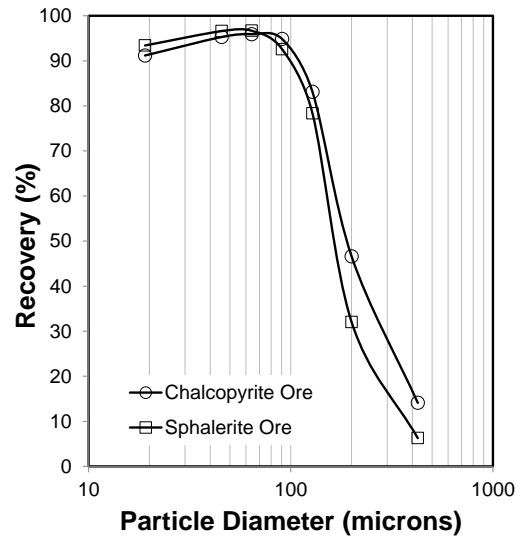


Figure 1 – Size-by-size recovery curves for sulfide ores upgraded by a laboratory flotation cell

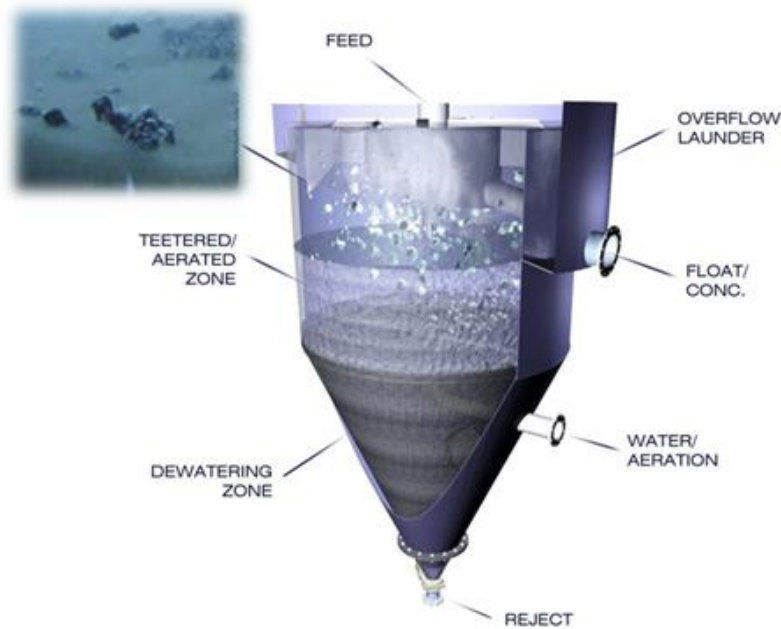


Figure 2 – Simplified schematic of the HydroFloat™ separator

EXPOSED GRAIN SURFACE AREA ANALYSIS

The percentage of exposed surface area of valuable mineral grains is an important parameter in flotation separations since exposed surfaces represent sites where bubbles can attach. Pioneering work conducted by Lin & Miller (2002) has shown that high resolution X-ray microtomography (HRXMT) can be used to quantify this important parameter provided that corrections are made for the partial voxel effect (Wang, 2016). The first step involved in the surface area analysis is to classify the internal and exposed grains within a particle. For example, Figure 3 shows an example of two- and three-dimensional images of grain size distributions for a copper ore particle. Particles can be considered to have three phases; gangue minerals, internal grains and exposed grains, as shown in Figure 4(a). To analyze the exposed surface area of valuable grains, it is important to extract both the particle surface and the surface of the exposed mineral grains from the three-dimensional images. As illustrated by Figure 4(b), the procedure for analysis of exposed grain surface area involves several steps. First, the three-dimensional whole particle phase and the grain phase are extracted, respectively. Then, the mesh surfaces of both the particle and the valuable grains are reconstructed based on the Marching Cubes method (Lorenson & Cline, 1987; Lewiner, Lopes, Vieira, & Tavares, 2003). The exposed surface area is determined by analyzing the overlapping vertices of the particle mesh surface and the grains mesh surface.

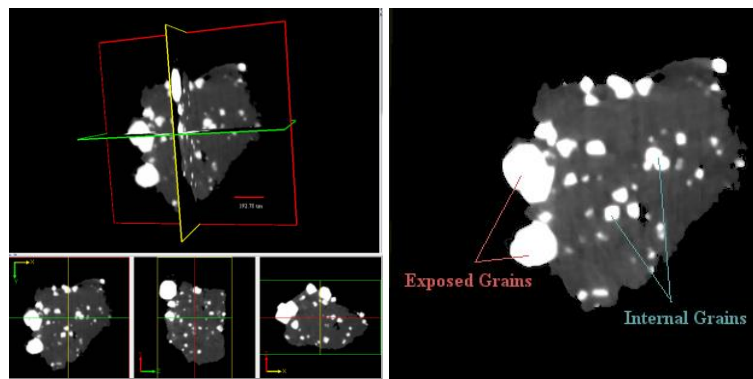


Figure 3 – Example of HRXMT images for a copper ore particle (841x500 μm)

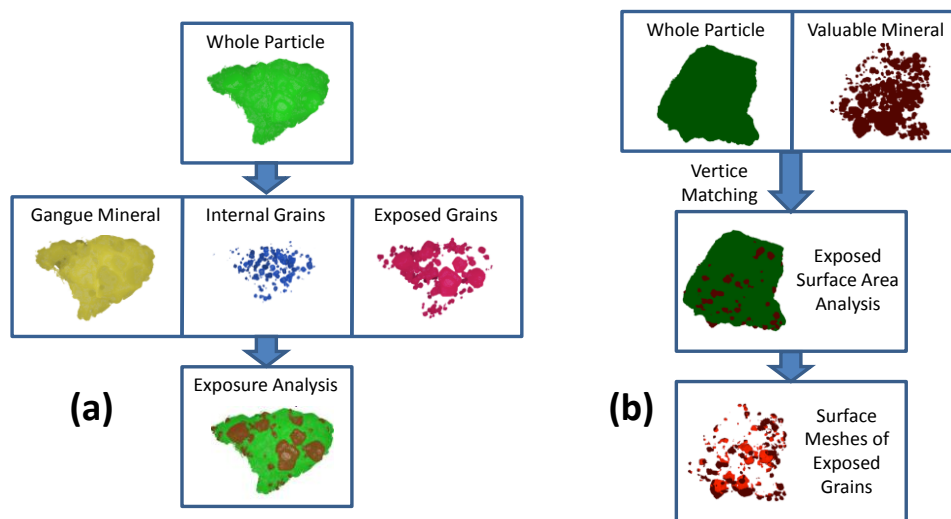


Figure 4 – Illustrations showing (a) internal and exposed grains for a 2-D sectional view of a copper ore particle (841x500 μm) and (b) exposed surface area analysis of a multiphase particle

EXPERIMENTAL

Laboratory and Bench-Scale Separation Tests

To compare the performance of conventional flotation and HydroFloat™ separators, a series of tests were conducted using a coarse sample of ore obtained from an operating gold concentrator. The as-received sample, which was collected from the underflow stream of the primary classifying hydrocyclones, was screened at 1000 µm to remove oversize material. Prior to flotation testing, the minus 1 mm fraction was deslimed at approximately 150 µm using a laboratory-scale (5x20 cm) Eriez CrossFlow™ hindered-bed classifier as described by Mankosa and Luttrell (U.S. Patent No. 6,264,040, July 24, 2001). The size distribution of the final flotation feed material is summarized in Table 1. As shown, more than 94% of the feed mass was larger than 212 µm for this particular sized/classified feed sample.

Table 1 – Flotation feed sample particle size distribution

Mesh Size		Particle Size (µm)		Weight	Cumulative (%)	
Pass	Retain	Pass	Retain	(%)	Pass	Retain
16	20	1000	850	9.99	100.00	9.99
20	35	850	500	35.24	90.01	45.23
35	70	500	212	48.98	54.77	94.21
70	--	212	0	5.79	5.79	100.00

After sizing of the as-received classifying cyclone underflow, the nominal 1000x150 µm fraction was split into two representative samples. The first split was subjected to conventional flotation using a benchtop (Denver) mechanical cell operated in batch mode. In this test, a 2-kg sample of the sized feed was conditioned for 3 minutes at 40% solids using 30 gm/t of Aerophine collector (Cytec 3416). The conditioned sample was diluted down to 20% solids and sufficient glycol-based frother was added to attain a frother concentration of 7 ppm in the flotation pulp. The flotation test was run until the froth was exhausted for floatable particles, which required about 15 minutes of total flotation time. The second split of feed sample was upgraded using a 15-cm diameter bench-scale Eriez HydroFloat™ separator. For the HydroFloat™ test, a 20-kg sample was conditioned for 3 minutes using Aerophine collector (Cytec 3416) at a dosage of 30 gm/t. The conditioned feed was metered into the separator using a vibratory feeder at a rate of 15 tonnes per hour per square meter. The feed slurry density was maintained at 50% percent solids by weight. A teeter water rate of 25 cubic meters per hour per square meter was found to be sufficient to maintain a properly fluidized bed for this sample. After ensuring that steady-state conditions were achieved, samples were collected of the feed, product and tailings streams. Feed, concentrate and tailing samples from each test program were screened into four size fractions and submitted for analysis to determine size-by-size recovery. Since the objective was to recover gold-bearing iron sulfides, the products were analyzed for total sulfur contents.

High-Resolution X-Ray Microtomography

A Micro XCT-400 high resolution X-ray microtomography (HRXMT) instrument, manufactured by Zeiss/Xradia, was used in this study. With high resolution analysis, multiphase particles can be described in three-dimensions down to less than 1 µm voxel resolution (Miller & Lin, 2009). The basic principle of operation is illustrated in Figure 5. Unlike conventional instruments, the Micro XCT-400 does not require the use of a small spot size X-ray source nor the need for the sample to be placed very close to the source to achieve sub one-micron imaging. With this configuration, it is possible to describe the structure and composition of a multiphase packed particle bed of up to 5 mm in diameter, resolving grain size, inclusions, pores and cracks with dimensions of 3 µm or smaller (voxel resolution in submicron range). The working distance between the X-ray source and sample may be varied up to 100 mm without sacrificing resolution.

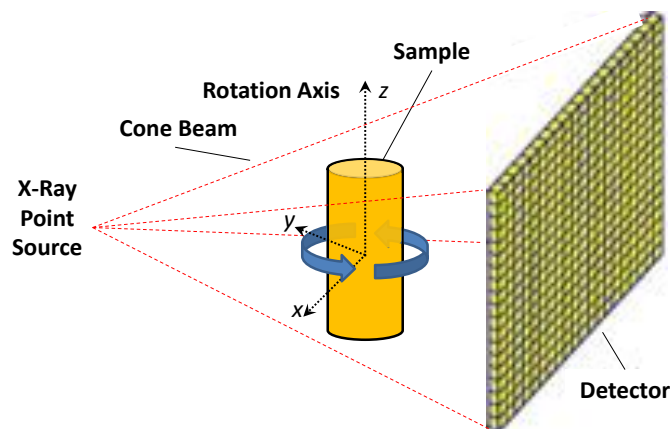


Figure 5 – Cone beam X-ray micro CT with point source and flat panel detector

Previous XMT research has demonstrated that grain exposure analysis is possible and can be used to explain the rate and extent of leaching as a function of the particle size distribution (Miller, Lin, Garcia, & Arias, 2003). Now, capabilities have been extended with software development to determine exposed grain surface area. In this study, an analytical procedure for the characterization of particle texture, namely exposed grain surface area analysis, has been used for the analysis of sized flotation concentrate and tailing samples from both benchtop conventional flotation and HydroFloat™ separation experiments. Specifically, how the texture of multiphase particles influences the separation efficiency during flotation is evaluated based on exposed grain surface area analysis from HRXMT data. Further, the characteristic texture of multiphase particles in each flotation product is determined and the effect of these textual features, specifically the surface area of exposed grains, on the flotation separation efficiency is discussed.

RESULTS AND DISCUSSION

Laboratory Separation Tests

Figure 6 compares the size-by-size separation data obtained from the test runs conducted using the HydroFloat™ separator and benchtop flotation machine. To ensure reliability, the data were mass balanced using a spreadsheet-based regression routine (Luttrell, 2004). The values plotted in Figure 6(a) show that the HydroFloat™ unit produced substantially higher mass yields (reported as a percentage of flotation feed) for all size classes examined in this study. Consequently, the HydroFloat™ provided a total concentrate yield of 21.6% compared to only 4.6% for the conventional flotation method. Due to the higher mass yields, a larger percentage of middling particles were floated in the HydroFloat unit, resulting in a corresponding decrease in the sulfur contents of the concentrate product. Figure 6(b) shows that the total sulfur contents of the conventional products were 2.2 to 8.1 percentage points higher in total sulfur, with the largest differences being observed for the 850x500 μm and 500x212 μm size fractions (i.e., relative differences in total sulfur contents of 8.1% and 5.9%, respectively). The lower sulfur contents of the size fractions recovered by the HydroFloat™ separator were indicative of the strong scavenging capability of this technology for the recovery of low-quality middlings containing small amounts of floatable mineral. This inherent characteristic of the HydroFloat™ separator resulted in substantially higher size-by-size recoveries for all size classes as shown in Figure 6(c). Overall, the total recovery for the conventional flotation machine and the HydroFloat™ separator were 42.9% and 68.1%, respectively. However, it is important to note that much of the increase in recovery for the HydroFloat™ technology was attributable to the superior recoveries of coarser particles in the plus 500 μm size fractions. As shown in Figure 6(d), the percentage increase in sulfur recovery afforded by the HydroFloat™ unit for the 500x212 μm size fraction was nearly 23% [i.e., $(77.9-61.0)/61.0 = +22.7\%$ increase]. This improvement increased to 111% for the 850x500 μm size fraction and jumped to over 1500% for the coarsest 1000x800 μm size fraction. These data suggest that the HydroFloat™ technology can be used to float very coarse particles historically thought to be unrecoverable by conventional flotation processes.

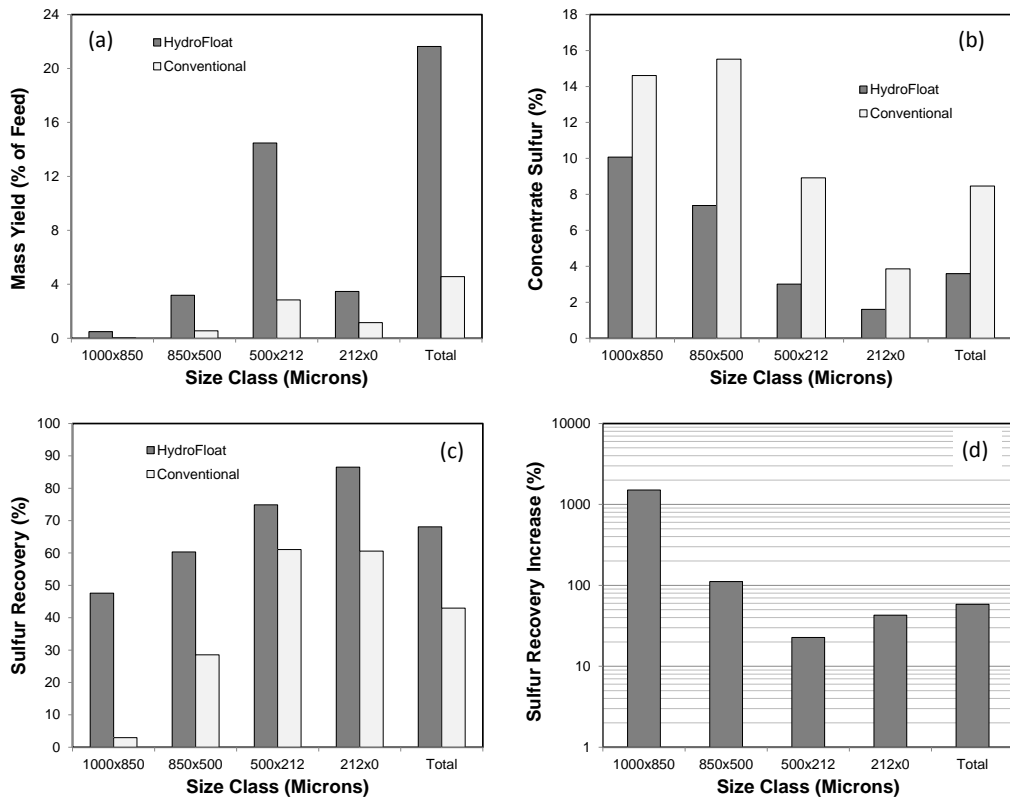


Figure 6 – Size-by-size separation data for HydroFloat™ and conventional flotation systems

HRXRT Analysis of Flotation Products

Exposed grain surface area analysis was used to analyze flotation products from the HydroFloat™ separator and conventional benchtop flotation cell. The 850x500 μm size class was selected for this study since the laboratory recovery data appeared to drop off sharply at this particle size. Three-dimensional images were obtained from the HRXMT scan of packed particle beds. First, the individual particles were extracted from the HRXMT data using suitable 3-D image processing. Then, the surface area of exposed grains of each particle was measured as described in the previous section.

Figure 7 shows the two-dimensional section and volume-rendered view of the original three-dimensional reconstructed image set (992x1013x790 voxels) obtained from HRXMT for selected particles from the HydroFloat™ concentrate and tailing products. As expected, based on the laboratory separation results shown above, the particles present in the tailing sample appear to be free of sulfide minerals or contain only minute amounts of finely dispersed mineral grains. In contrast, the images of particles present in the concentrate all contain sulfide minerals intermixed within the host gangue matrix of composite “middling” particles. Similar trends can be seen in Figure 8 for the three-dimensional images of individual particles and exposed surfaces for the HydroFloat™ concentrate and tailing samples. For demonstration purposes, only nine particles from the concentrate and tailing products are shown in this image set. The exposed gangue mineral phase is shown in green and the exposed valuable mineral phase is shown in red. These images very clearly show that little or no exposed grain surfaces of sulfide minerals are present in the HydroFloat™ tailing samples.

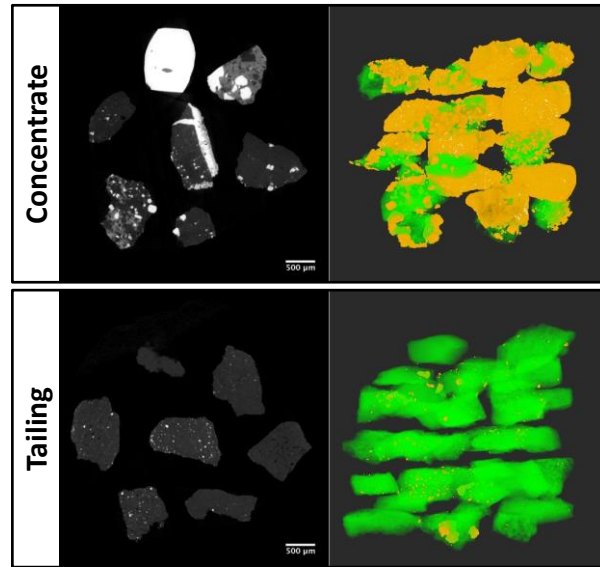


Figure 7 – Two-dimensional (left) image and volume-rendered view (right) of 850x500 µm particles of HydroFloat™ concentrate and tailing products (gangue = green, valuable mineral = brown)

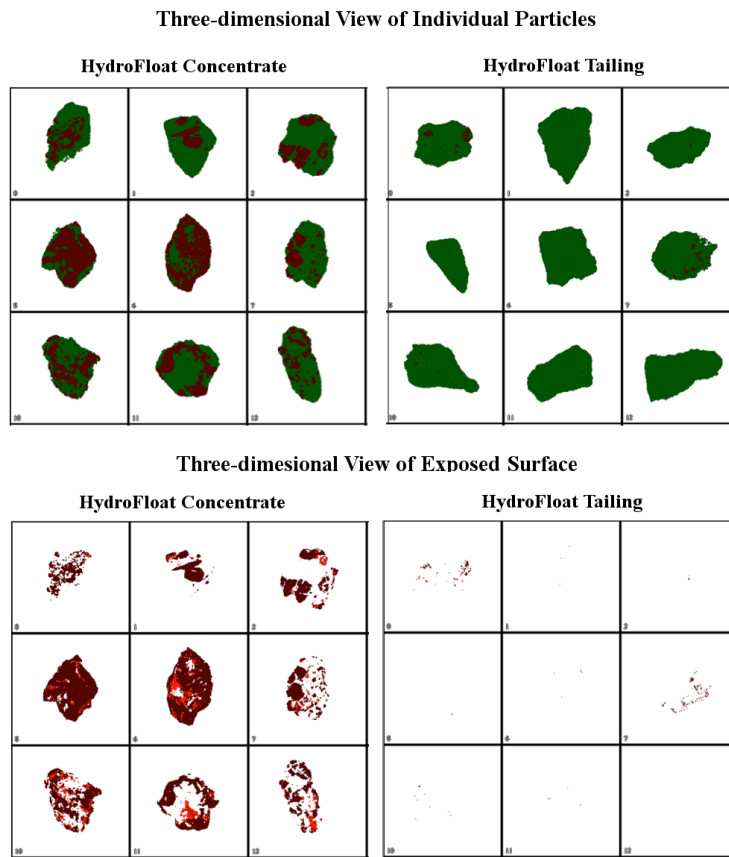


Figure 8 – Three-dimensional views of 9 selected particles and exposed surface of 850x500 µm particles of HydroFloat™ concentrate and tailings (gangue surface = green, exposed valuable mineral surface = red)

Figure 9 shows the distribution of exposed grain surface area for individual particles from the concentrate and tailing products generated by the HydroFloat™ separator and benchtop flotation machine. The data are plotted as the cumulative frequency of exposed surface area of sulfide minerals identified in each sample. Figure 9(a) shows that the particles reporting to the HydroFloat™ concentrate required far less exposed grain surface area than particles reporting to the benchtop conventional concentrate. The sharp upturn in the frequency curve for the HydroFloat™ separator occurred at about 10% exposed grain surface area, while the sharp upturn for the benchtop flotation cell did not occur until about 55% exposed grain surface area. In fact, the data show that less than 50% of the particles present in the HydroFloat™ concentrate had grain surface exposures of less than 19%, while 50% of the particles in the benchtop conventional concentrate had more than 72% exposed grain surface area. This large difference shows that the HydroFloat™ was capable of recovering a higher proportion of middlings with low grain surface area exposure as compared to the conventional benchtop flotation cell. The cumulative frequency plots for the tailing products also reflect the superior scavenging ability of the HydroFloat™ separator. Based on the cumulative frequency curves plotted in Figure 9(b), the HydroFloat™ tailing sample was found to have 85% of particles with less than 0.5% exposed grain surface area and about 95% of particles with less than 1% exposed grain surface area. In comparison, the conventional benchtop tailing sample was found to have more than 70% of particles with less than 0.5% exposed grain surface area and about 80% of particles with less than 1% exposed grain surface area. More importantly, the frequency data suggest that no particles with exposed grain surface areas of 1.5% or higher reported to the HydroFloat™ tailing product. The conventional benchtop flotation results were less impressive and indicated that exposed grain surface areas of about 6% or higher were required for complete recovery of sulfide-bearing particles for this ore.

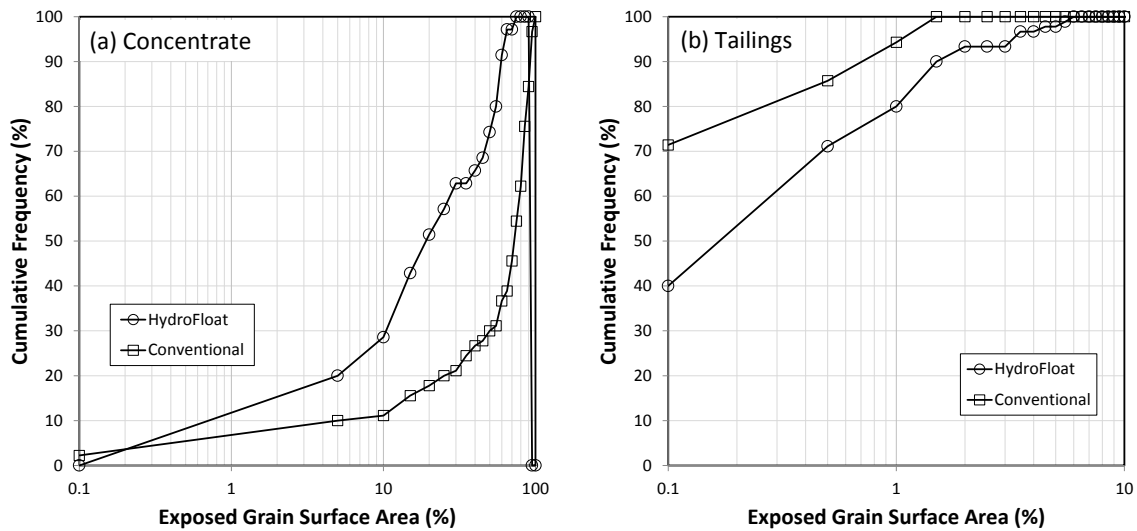


Figure 9 – Cumulative distribution of exposed grain surface area for particles from the concentrate (a) and tailings (b) generated by the HydroFloat™ separator and conventional benchtop flotation machine

SUMMARY AND CONCLUSIONS

The HydroFloat™ separator has been successfully demonstrated in commercial application for the industrial upgrading of coarse industrial minerals such as coal, potash and phosphate. Based on this success, testing has now turned towards potential applications of this unique technology in other mineral systems where traditional flotation systems are limited by an upper particle size constraint. The specific goal of this recent effort has been to determine whether the HydroFloat™ technology can be utilized to dramatically improve the recovery of coarse low-grade sulfide minerals that have historically been lost in traditional processing schemes involving other types of flotation machines. In the current study, high resolution X-ray microtomography (HRXMT) was used to experimentally compare the degree of exposed grain surface area necessary to recover very coarse (850x500 μm) particles using both the HydroFloat™

separator and a conventional mechanical flotation machine. The resultant data conclusively show that the concentrate produced by the HydroFloat™ separator contained a much greater proportion of low-grade composite middling particles than the concentrate generated by the conventional flotation machine. More than half of the particles present in the HydroFloat™ concentrate were found to have grain surface exposures of less than 19%, while half of the particles in the conventional concentrate had less than 72% exposed grain surface area. The HRXMT data also showed that no particles with exposed grain surface areas of 1.5% or higher reported to the HydroFloat™ tailings, while the analysis of the conventional flotation tailings showed that particles with as much as 6% exposed grain surface area were still lost in the tailings product despite floating to exhaustion. The data collected in this study suggest that the HydroFloat™ separator may provide a viable option for increasing concentrator throughput by increasing the grinding mill capacity as a result of the coarser grind size and lower extent of liberation that can be effectively dealt with by this unique flotation technology.

REFERENCES

- Jameson, G.J., Nguyen, A.V., & Seher, A. (2007). The flotation of fine and coarse particles. In N. Fuerstenau, G. Jameson, & R.-H. Yoon (Eds.), *Froth flotation – A century of innovation* (pp. 339-372). Littleton, Colorado, USA: SME.
- Kohmuench, J.N., Mankosa, M.J., Kennedy, D.G., Yasalonis, J.L., Taylor, G.B., & Luttrell, G.H. (2007). Implementation of the HydroFloat technology at the South Fort Meade mine, *Minerals and Metallurgical Processing*, 24(4), 264-270.
- Kohmuench, J.N., Mankosa, M.J., Yan, E.S., Wyslouzil, H., & Christodoulou, L. (2010). Advances in coarse particle flotation – Industrial minerals. In *Proceedings 25th International Mineral Processing Congress, 2010* (pp 2065-2076). Victoria, Australia: The Australasian Institute of Mining and Metallurgy.
- Kohmuench, J.N., Thanasekaran, H., & Seaman, B. (2013, July). *Advances in coarse particle flotation: copper and gold*. Paper presented at AusIMM MetPlant Conference, Perth, Western Australia.
- Lewiner, T., Lopes, H., Vieira, A.W., & Tavares, G. (2003). Efficient implementation of marching Cubes' cases with topological guarantees. *Journal of Graphics Tools*, 8, 1-16.
- Lin, C.L., & Miller, J.D. (2002). Cone beam X-ray microtomography – A new facility for three-dimensional analysis of multiphase minerals. *Minerals and Metallurgical Processing*, 19(2), 65-71.
- Lorensen, W.E., & Cline, H. (1987). Marching Cube: a high resolution 3D surface construction algorithm, *SIGGRAPH '87*, 163-169.
- Luttrell, G.H. (2004). Reconciliation of excess circuit data using spreadsheet tools. *Coal Preparation - A Multinational Journal*, 24(1-2), 35-52.
- Mankosa, M.J., & Luttrell, G.H. (2001). *Hindered-bed separator device and method* (July 24, 2001). U.S. Patent No. 6,264,040. Washington, DC: U.S. Patent and Trademark Office.
- Mankosa, M.J., & Luttrell, G.H. (2002). *Air-assisted density separator device and method*, (July 30, 2002). U.S. Patent No. 6,425,485. Washington, DC: U.S. Patent and Trademark Office.
- Miller, J.D., & Lin, C.L. (2009). High Resolution X-ray Micro CT (HRXMT) – Advances in 3D particle characterization for mineral processing operations. In D. Melhotra, P.R. Taylor, E. Spiller, & M. Levier (Eds.), *Recent advances in mineral processing plant design* (pp. 48-59). Littleton, Colorado, USA: SME.
- Miller, J.D., Lin, C.L., Garcia, C., & Arias, H. (2003). Ultimate recovery in heap leaching operations as established from mineral exposure analysis by x-ray microtomography, *International Journal of Mineral Processing*, 72, 331-340.
- Wang, Y. (2016). *Improved 3D image processing for tomographic analysis of multiphase packed particle beds* (Doctoral dissertation), University of Utah, Salt Lake City, Utah, USA.