IMPROVED FLOTATION OF FINE PGM TAILINGS WITH A HIGH SHEAR CAVITATION DEVICE

Victor Ross[1], Adrian Singh[2], Musa Dlame[1], Kevin Pillay[1]

1 Mineral Processing Division, Mintek, 200 Malibongwe Drive, Randburg 2125 South Africa
2 GoldOre Pty Ltd, 2 Cascades, Russel Street, Benoni 1501 South Africa

ABSTRACT

A significant amount of liberated fine valuable particles is lost to flotation tailings streams due to inefficient collection by air bubbles and deactivation of surfaces by oxidation and slimes. Extensive research has been done in this area to improve recoveries, including the use of micro bubble generators and dissolved air flotation, the agglomeration of fines, sonication and attritioning to clean surfaces, removal of oxidation products by chemical methods, the activation of surfaces by suphidisation and changes in Eh, and the use of alternative collectors.

An exciting and practical prospect is the use of high shear cavitation devices (HSCDs), in which the feed slurry is intimately contacted with air in a high pressure environment, typically a series of venturi aerators. This promotes cavitation and the formation of ultrafine bubbles on particle surfaces, which is believed to aid the agglomeration and subsequent recovery of the valuable fines by normal sized bubbles. In addition, it is expected that successive passes of slurry through the reactor aids the cleaning of particle surfaces, and that additional liberation through attrition may also occur as a result of the severe inter-particle action. A fourth mechanism is believed to be due to the significant increase in gas holdup in the pulp phase when compared to that in conventional cells, resulting in a much changed hydrodynamic environment.

This paper details recent investigations that have been undertaken at Mintek on the Mach HSCD reactor, using rougher, cleaner and recleaner feed obtained from a UG2 PGM tailings operation to better understand these mechanisms. The results suggest that the dominant mechanism responsible for the improved recovery was due to the cleaning of particle surfaces, not only activating valuable mineral surfaces but presumably also deactivating that of the gangue. This was evident from the results of tests in which samples were preconditioned through the reactor, followed by bench batch flotation tests under conventional conditions. Significant improvements in the final fitted recovery Rmax, together with a drop in mass pull, were observed for the optimum number of passes for the various feed conditions. It is unclear at this stage to what extent selective liberation of PGMs from the chromite grains, or the nucleation of micro bubbles on the particle surfaces and the resultant aggregation of these particles, contribute to the overall recovery. Further testwork is underway to investigate the various mechanisms more closely, and expand the potential range of applications of this technology.

INTRODUCTION

It is well established through research and practical experience that the recovery of fine and ultrafine particles, typically less than 10 to 20 micron in size, by flotation is a challenge (Yoon et al., 1989). Due to their very low mass and inertia, the collision efficiency with air bubbles is low due to the inability of the particle to penetrate the liquid streamlines around a bubble. Hence the probability of contact is often regarded as the rate-determining step in flotation of ultrafine particles, and this mostly results in a significant mass pull due to the prolonged flotation time that is required to effect acceptable recoveries in flotation circuits.

This problem has in recent years become ever more pronounced due to the use of fine and ultrafine grinding (UFG) of flotation feed to achieve better liberation of valuable minerals, especially in lower grade or complex ores. Rule and Anyimadu (2007) demonstrated that after addressing liberation issues with UFG in stirred milling, an alarmingly high proportion of <10 µm and particularly <5 µm fully liberated Platinum Group Minerals (PGMs) were being lost to tailings. This is consistent with the limitations of conventional flotation at finer size fractions. They commented that this problem was unlikely to be solved by introducing more power into conventional flotation cells and predicted that different flotation technology would solve this problem eventually. It is well-known that especially conventional flotation machines are less efficient in the fine to ultrafine region, and that conditions of high shear and micro-turbulence are required to promote particle-bubble interaction in such events.

The flotation of tailings material in retreatment operations make this challenge even more daunting due to coating of the valuable particle surfaces by oxidised and oxyhydroxide layers that have formed due to prolonged exposure to the atmosphere or slimes. Various approaches to mitigate this problem have therefore been undertaken, including:

- Generation of micro- and nano-bubbles, and the use of dissolved air flotation (Calgaroto et al., 2014; Martinez-Gomez et al., 2013; Qi and Aldrich, 2002)
- Seed or carrier flotation (Subrahmanyam and Forssberg, 1990; Tabosa and Rubio, 2010;), such as spiking the pulp with concentrate so as to promote the formation of agglomoerates that are easier to recover by air bubbles
- Sonication to clean particle surfaces (Aldrich and Feng, 1999; Qi and Aldrich, 2002)
- High intensity conditioning (Bulatovic and Salter, 1989; Tabosa and Rubio, 2010; Chen et al., 1999)
- Electrochemical approaches such as changing Eh in order to promote formation of dixanthogen, dissolution of oxidation products by lowering the pH, activation by sulphidisation or Cu(II), and the use of alternative collectors to float oxides and hydroxides.

Another type of high intensity conditioning device which offers a practical solution to the above challenges and already have found its way to commercial application in the South African PGM industry, is high-shear cavitation devices (HSCDs). Typical examples are the Eriez CavTube (Oliveira et al., 2017) and the Mach reactor (Singh, 2016). These devices typically consist of one or more venturi aerators in series or a multitude of parallel, restricted apertures in which intimate contact is effected between the fine particles and the very fine bubbles that are formed as a result of the high shear. This results in a hydrodynamic environment in the pulp zone which is quite different to that normally observed with conventionally aerated mechanical flotation cells. The significantly increased gas holdup that develops within the pulp at the high gas fluxes and very fine bubbles are believed to form a sort of 'safety net' in which particles that detach could readily re-attach (Dickinson and Galvin, 2014). An added opportunity offered by these devices is an increased activation of the surfaces of the hydrophobic particles as a result of the intense inter-particle attrition as the slurry stream moves through the successive restrictions under conditions of high turbulence. As will be discussed further below, such a mechanism can be exploited by applying the HSCD as a high-energy attritioner, prior to employing its benefits in micro-bubble generation and improved particle-bubble attachment.

Mechanisms

Relatively little information is currently available in the literature regarding the various mechanisms that affect the efficiency of high shear conditioning devices. However, the preliminary results of earlier work at Mintek on a variety of ores, together with published literature on hydrodynamics and flotation of fines, suggest at least four distinct mechanisms. These mechanisms, discussed further below, would play a more or less dominant role depending on the particular type of ore and its condition as far as oxidation, slimes and other de-activating species are concerned.

Surface cleaning

HSCDs can be used as effective inter-particle attritioners by successive recirculation of feed slurry through the device, aiding in the removal of oxidised layers and any slime coatings from the surface of particles. This mechanism is believed to be a major contributor to the enhanced flotation response that has been observed during earlier tests on a variety of ores. In these tests, the metallurgical response before and after pre-conditioning of the feed through the Mach reactor in the absence of air were compared by floating these samples in a conventional mechanical flotation cell. As such, the only difference between these tests was the way in which the samples were preconditioned, and other factors such as increased gas holdup and formation of micro-bubbles were deliberately designed out of the experimental procedure. Clear evidence of freshly activated surfaces of valuable mineral was found via the significantly increased recoveries and rates of flotation.

Another, equally important, observation was the significant decrease in mass pull for samples that have been preconditioned by successive passes through the reactor. A plausible explanation for this would be that the attritioning through the Mach also resulted in the cleaning of gangue mineral surfaces, hence removing traces of hydrophobic minerals such as talc and other adsorbed species that could lead to activation of the gangue once collector is added.

Increased liberation

As a result of the repeated and intensive inter-particle interaction during their passage through the reactor, it is likely that attritioning could increase the liberation of valuable particles, such as fine PGMs being associated with chromite particles on grain boundaries, and thus lead to increased valuable mineral recovery. In addition, partly liberated valuable grains could be exposed increasingly as the coating by gangue is worn away successively. Earlier tests in which the particle size distribution before and after preconditioning was compared, indicated an increased amount of fines being generated, thus lending credibility to such a mechanism. The extent to which for instance a mechanical attritioner could have the same effect at an equivalent level of energy consumption is the focus of future testwork.

Increased gas holdup and bubble flux

The combined effects of a higher gas flow and the formation of micro bubbles when compared to a conventional flotation cell translate into higher bubble flux and hence improved flotation kinetics. An added effect is the significant increase in gas holdup in the pulp, where levels of 50% have been measured compared to the ~10 to 15% that is typical of conventional mechanically agitated cells. The high gas holdup correspond well with the levels measured by Dickinson and Galvin (2014) in the bubbly foam regime of the reflux flotation cell, and create conditions in which entrainment is seemingly reduced compared to the conventional case where bubbles rise in the pulp in very much an unhindered fashion.

Nucleation and agglomeration

As pointed out by Singh (2016), HSCDs impart significantly higher shear and energy dissipation rates to the feed compared to a conventional mechanical flotation cell. The design and operating conditions of the reactor is believed to promote hydrodynamic cavitation (Sobhy and Tao, 2013) and the formation of ultrafine bubbles on particle surfaces, which aids the agglomeration of fines and hence their subsequent recovery as effectively larger particles. According to Bernoulli's principle, when a liquid flows through a constriction the velocity increases, causing the instantaneous pressure to fall. At a certain critical velocity the instantaneous pressure will fall below the vapour pressure of the liquid causing tiny cavities/bubbles to form on impurities in the liquid (Hu et al., 1998). In slurry systems, these impurities can be hydrophobic mineral particles, which could have minute quantities of gas trapped on the surface as it exits a milling circuit. This could act as nucleation points for cavitating bubbles, imploding into a multitude of pico-bubbles as soon as the static pressure increases. Cavities can be partially stabilised by diffusion of dissolved gases into the cavities and the addition of a frother.

However, the pico-bubbles cannot provide sufficient buoyancy to float mineral particles and hence the involvement of flotation size bubbles, typically in the range of 600 µm to 2 mm, is still required (Tao, 2005). Therefore it is suggested that the pico-bubbles be introduced into flotation cells to complement rather than replace flotation size bubbles (Nesset et al., 2006). Research has shown that the ageing of micro (pico) bubbles as well as flotation sized bubbles was detrimental to particle-bubble attachment and that future the optimum flotation conditions would be obtained under conditions in which the two are co-generated.

The proposed mechanism, depicted graphically in Figure 1, involves nucleation of micro-bubbles, stabilised by frother addition, on the surfaces of fine hydrophobic particles. Intensive mixing of the slurry would lead to the formation of aggregates of hydrophobic fines, held together by the micro-bubbles through a bubble bridging mechanism. Evidence of the value of providing hydrophobic 'seed' particles to collect ultra-fines was for instance demonstrated by Tabosa and Rubio (2010). The final step in the process is the presentation of an effectively larger and more homogeneously hydrophobic particle to a normal sized flotation bubble, resulting in an increased collision and attachment efficiency, after which the aggregate is levitated to the surface of the pulp and transferred into the concentrate via the froth.

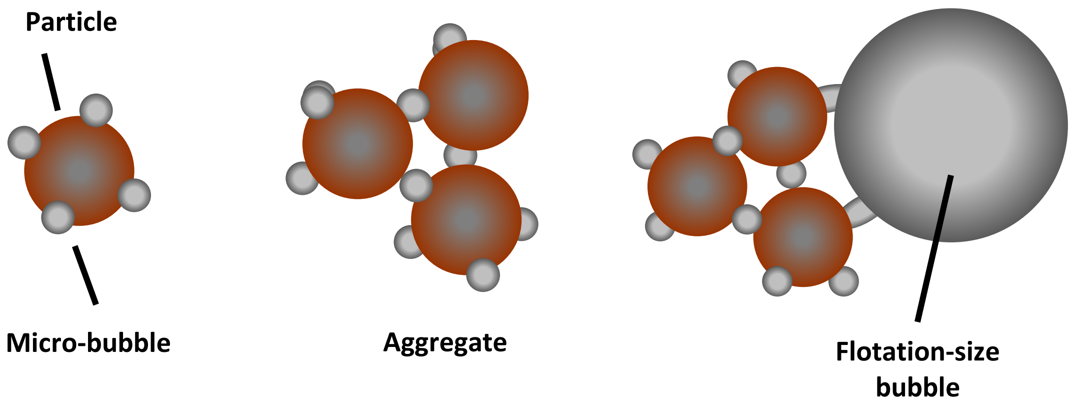

Figure 1: Proposed mechanism of particle aggregation and levitation (after Singh, 2016). Nucleation of micro bubbles on fine particle surfaces is followed by agglomeration of the hydrophobic fines and subsequent collection by normal size bubbles (not drawn to scale).

EXPERIMENTAL

Ore samples

Three samples from a PGM tailings treatment operation on the western limb of the Bushveld Complex in South Africa, *viz* a cyclone overflow (rougher feed), cleaner feed, and recleaner feed, were supplied to Mintek in slurry form. These were split representatively into 20 L buckets by syphoning, and kept in slurry form for the duration of the testwork. Approximately 10 kg of each was sub-sampled for head analyses, showing good reproducibility and averaging a 4E assay of 0.69 g/t, 2.22 g/t and 10.6 g/t respectively. Slurry densities varied from 22% by mass for the cyclone overflow to 18% for the cleaner feed and 13% for the recleaner feed. The particle size distributions of the three samples are shown in Figure 2, the rougher feed material being relatively coarse at less than 60% passing 75 micron. Both the cleaner and recleaner samples were however very fine at in excess of 80% passing 25 micron and thus, despite their higher feed grade and thus being relatively well liberated, being problematic to achieve reasonable flotation kinetics.

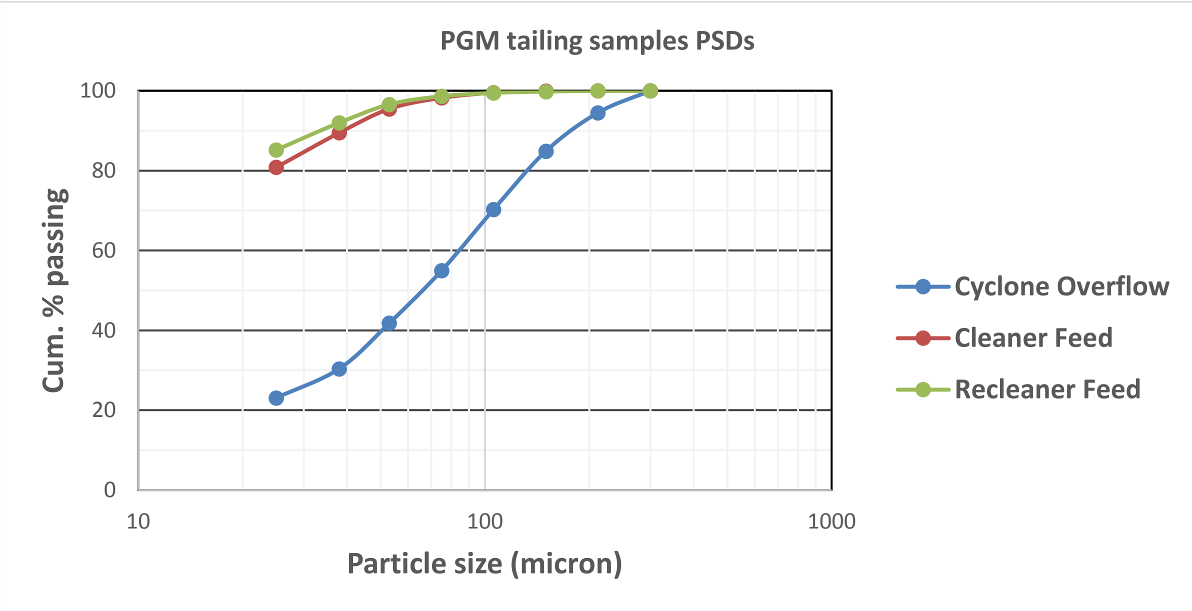

Figure 2 Particle size distributions for the three UG2 tailings samples. 4E head grades were 0.69 g/t, 2.22 g/t and 10.6 g/t respectively.

Mach reactor

A schematic representation of the Mach reactor is shown in Figure 3. The reactor features four custom-designed nozzles that are connected in series: a medium speed mixing nozzle feeds into two high-speed cavitating nozzles which in turn jet into a collection nozzle at the exit of the reactor. External air is injected under pressure between each nozzle, at around 5 bar. This design maximises cavitation in the high speed nozzles while also providing an environment in the collection nozzle to promote aggregation of hydrophobic fine particles via the proposed bubble bridging mechanism. The collection nozzle, which incorporates features of a plunging jet, also generates flotation size bubbles which attaches to particle-bubble aggregates to complete the collection process and provide for a higher rate of flotation in a conventional flotation cell (Zhou et al., 1997). In addition, the reduced bubble size translates to a significantly higher bubble flux than in conventional machines, together with higher shear and energy dissipation rates, which should lead to better flotation of fines. The mechanical flotation cell thus provides mainly the vehicle for the separation of froth from slurry through levitation of the particle-bubble aggregates (Changgen and Bahr, 1992). Reasons for selecting this reactor for the test programme included ease of operation and reduced downtime due to blockages and wear, as well as the fact that it could be scaled quite easily and effectively so as to enable testwork at both a laboratory and pilot scale.

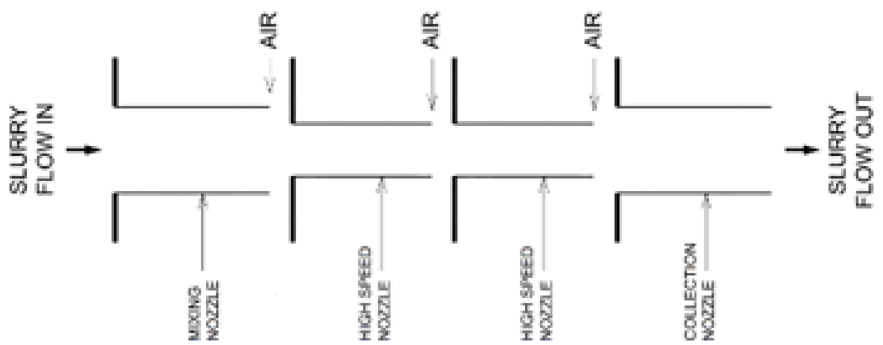

Figure 3 Schematic of Mach reactor (Singh, 2016).

Test procedure

The testwork entailed firstly a conventional batch rougher rate flotation test that was performed on each slurry sample in a 10L laboratory Denver cell in order to set the respective baselines. In each case the slurry was conditioned for 4.5 minutes (SIBX at 200 g/t, KU433 depressant 100 g/t, XP200 frother 40 g/t) before flotation commenced, concentrates being collected after 1, 3, 7, 14 and 30 minutes of flotation. In subsequent tests (Figure 4), the feed sample was preconditioned with the same reagents and dosage in the conditioning tank before the slurry was passed through the Mach for 5, 10, 15, 20 and 30 passes respectively by recirculation for the required period of time. The slurry flowrate was maintained at around 45 L/min. As such, a clear comparison could be made with the baseline conditions (where no surface cleaning occurred). While circulating the feed sample through the Mach, a slight positive air flow was maintained in order to prevent slurry pushing into the air lines. It should be noted that the reactor was therefore used principally as a feed conditioning device, rather than focused on aiding flotation for instance through the creation of small bubbles and promoting a high gas holdup in the pulp phase. However, the possibility of stable micro-bubbles being formed on the particle surfaces, and remaining intact for sufficiently long so as to impact on the particle collection efficiency during flotation in the mechanical cell, cannot be discounted altogether. The gas holdup in the pulp however was at conventional levels (coming only from the impeller of the mechanical cell); a further series of tests will be aimed at understanding the effect of the changed hydrodynamics more clearly.

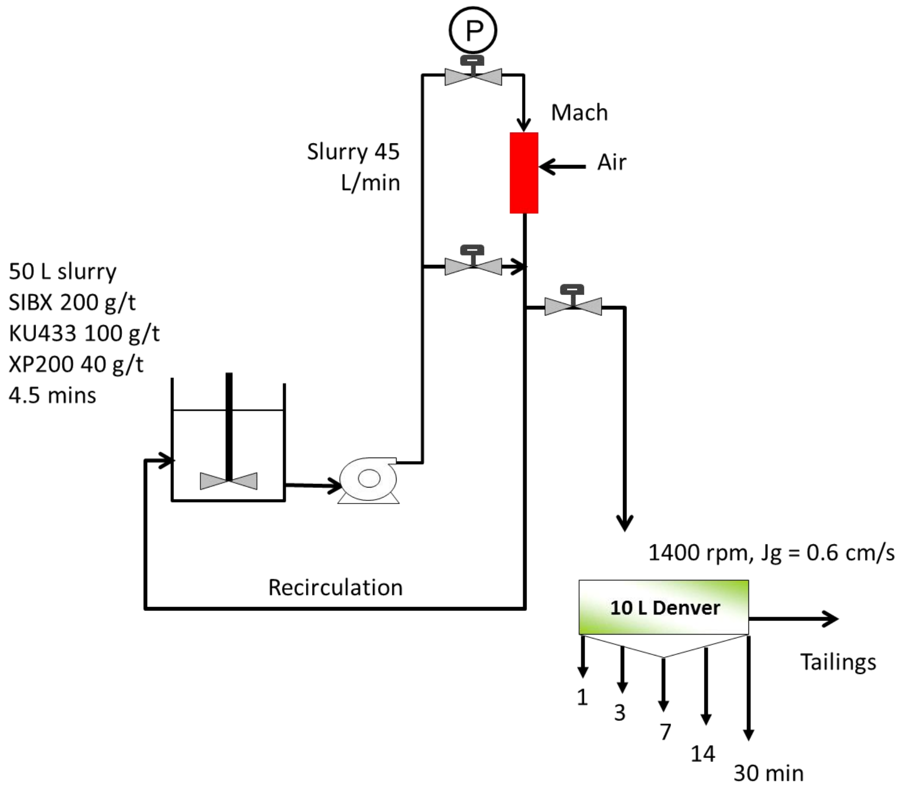

Figure 4 Experimental setup for flotation tests.

RESULTS AND DISCUSSION

Rougher

Summarised flotation results for the cyclone overflow (rougher feed) sample are presented in Figures 5a and b. The kinetic response for the various tests was quite consistent, the initial gains that were made in each case carrying through to the total flotation time of 30 minutes, at which time the float was still not complete. The mass pull for this set of tests ranged between 4.8 and 7.9 %; at a mass pull of 6.6% the overall recovery for the baseline test after a flotation time of 30 minutes was 49% with a corresponding 4E grade (combined Pt, Pd, Rh and Au) of 4.9 g/t. After 5 passes of preconditioning through the reactor, the recovery increased to 52% at an overall grade of 6.5 g/t, indicating an increased rejection of the gangue as the PGMs also became progressively more floatable. As mentioned earlier, the reduced gangue recovery in this case was presumably due to the deactivation of surfaces rather than increased gas holdup, since the sample was floated in a batch mode in the 10 L cell after conditioning. Future tests will also focus on water recoveries to better understand the role of entrainment. A 10 pass preconditioning yielded optimum recovery as it increased to 63%, at an improved grade of 7 g/t compared to the overall baseline grade of 5 g/t.

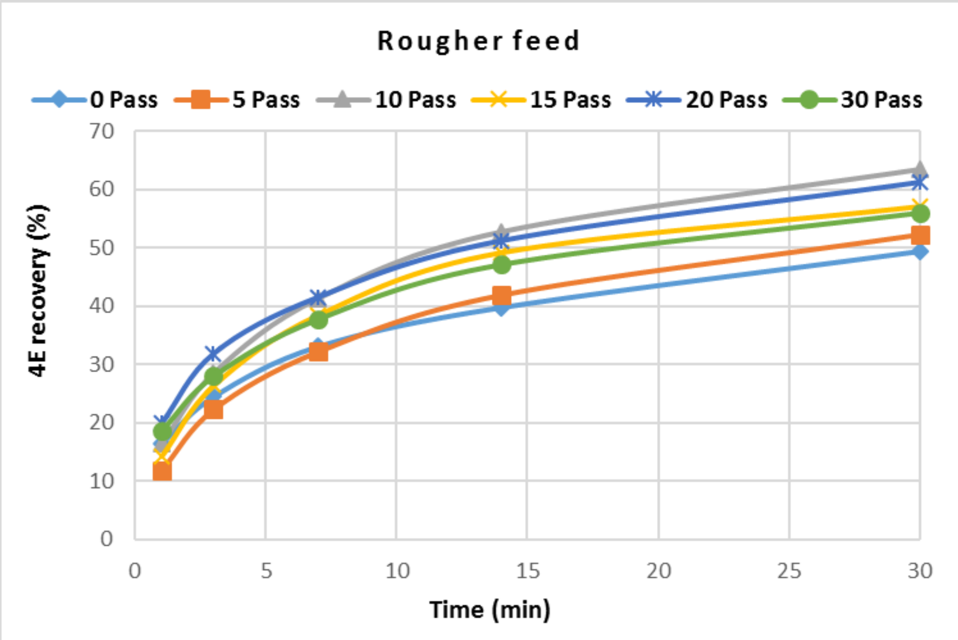

Figure 5a Recovery kinetics of the rougher feed sample.

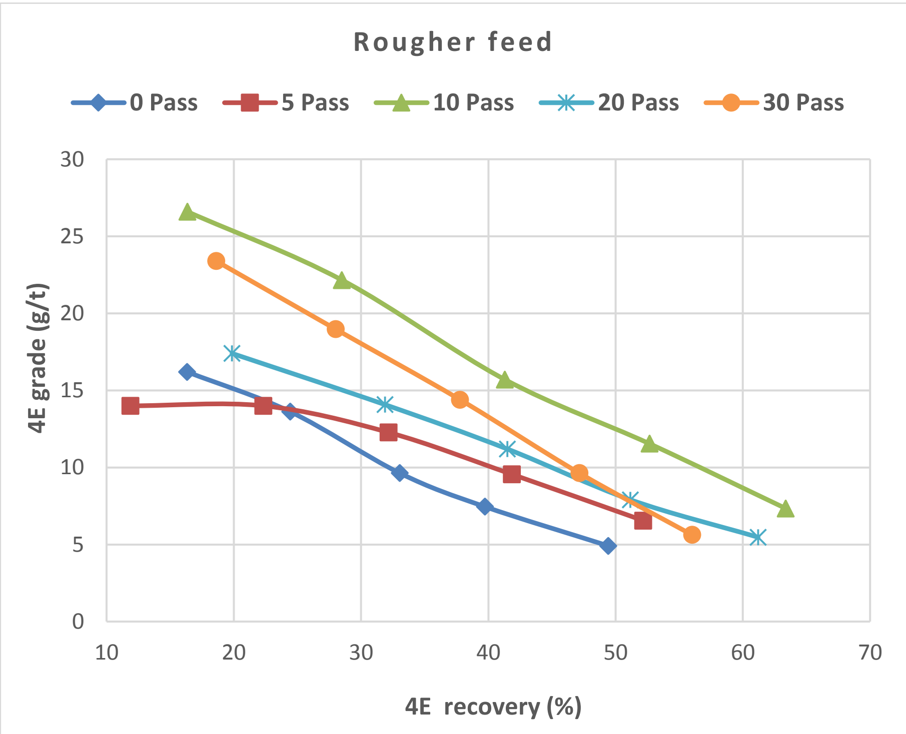

Figure 5b Grade-recovery results for the rougher feed sample.

Further increasing the preconditioning (i.e. to 15, 20 and 30 passes) enhanced recovery compared to the baseline, but not to the same extent as was achieved for the 10-pass conditions. Here, final recoveries ranged between 56 and 61%, representing an average 10% improvement in overall recovery compared to the baseline and being achieved at a similar overall concentrate grade of around 5 g/t (i.e. an upgrading ratio of 7).

Cleaner

The pronounced effect of preconditioning of the feed through the Mach HSCD on the flotation kinetics, grade-recovery relationships and the upgrade ratio of the PGM tailings is further demonstrated in Figure 6 for the cleaner feed. It is evident that the optimum kinetics and overall 4E grade and recovery in this case occurred after around 15 passes of the feed slurry through the reactor, rather than the ~10 passes as was the case for the rougher.

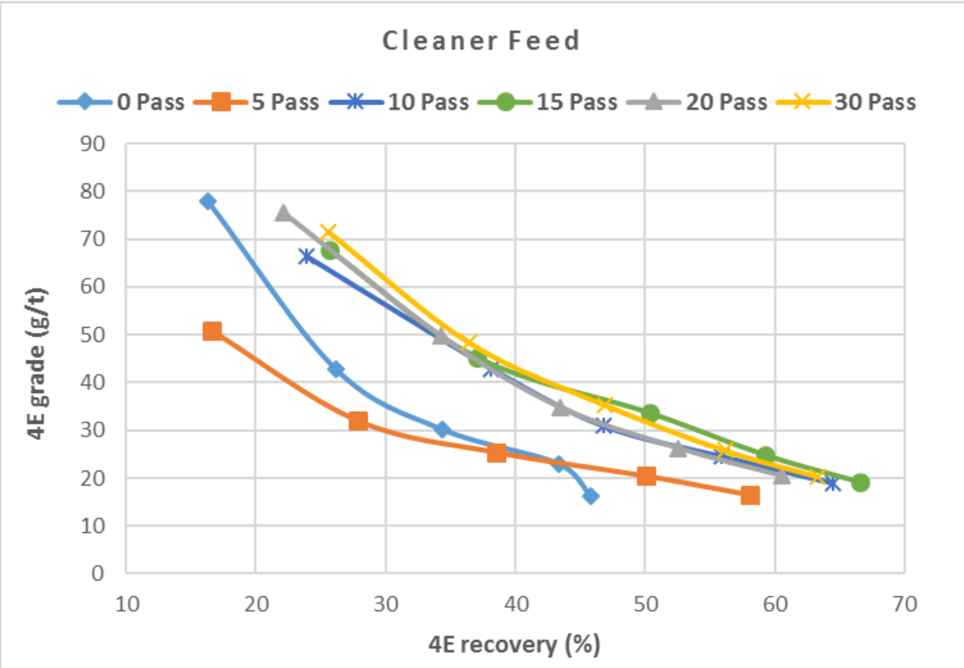

Figure 6 Grade-recovery results for the PGM cleaner feed material.

The mass pull for the six tests ranged between 7.1 and 8.6%, slightly up on that of the rougher. After the total residence time of 30 minutes in the mechanical flotation cell, a concentrate of 16 g/t and 46% recovery was attained for the baseline conditions, representing an upgrade ratio of around 8. A 5 pass preconditioning enhanced the overall recovery immediately by a significant 12% to 58%, while maintaining the overall grade. Increasing the preconditioning to 10 passes improved the overall recovery and grade further to 64% and 19 g/t respectively, whilst an additional 5 passes further improved the recovery to 67% accompanied by a slight increase in grade. As observed for the rougher, longer pre-conditioning resulted in a decreased recovery, presumably because of the generation of ultrafine particles that started interfering with the collection of valuables, or deterioration of reagents at the increased pulp temperatures.

Recleaner

Figures 7a and b describe the kinetics and grade-recovery relationships for the recleaner feed sample, again demonstrating the significant impact of preconditioning in a high-shear environment on the flotation efficiency. As was observed for the rougher and the cleaner samples, the significantly increased kinetics of the PGM recovery after preconditioning carried through systematically to the final flotation time. Sharp increases in final recoveries are noted; in this case, contrary to the results observed for the other samples, increased preconditioning time systematically increased the performance across the full range of conditions tested, the highest overall recovery of 77% being achieved after between 20 and 30 passes.

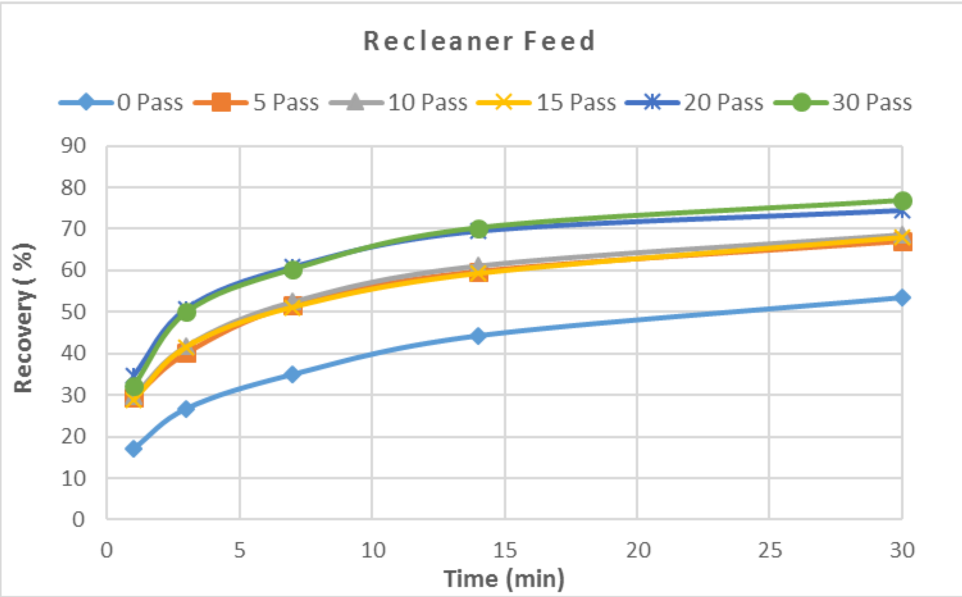

Figure 7a Kinetic response of the recleaner feed sample at different conditions.

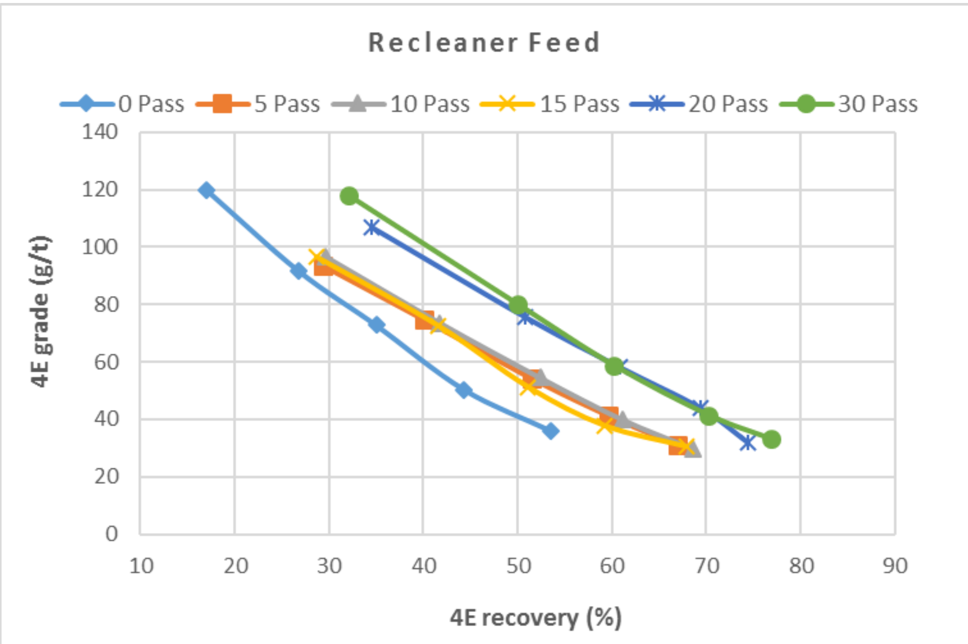

Figure 7b Grade-recovery results for the recleaner feed.

As before, the baseline test (at a total residence time of 30 minutes) yielded the lowest PGM recovery of 54% at an overall grade of 36 g/t. Preconditioning with the Mach for 5 passes significantly enhanced the recovery (54% to 67%) but the overall concentrate grade was reduced to 31 g/t due to the higher mass pull.

Kinetic parameters

Flotation kinetics data of the baseline and optimum Mach preconditioning conditions were fitted to a modified Kelsall model, using the Excel Solver routine. Both the data of valuable species (4E) and that of gangue (for simplicity, considered in this case to be the total mass of material reporting to the concentrate since the comparative mass of PGMs and sulphides is negligibly small) were modelled. The model characterises the floating mineral species into two rate classes corresponding to slow and fast floating components, and is of the form:

$$R = R_{max} [Q_f (1 – \exp (-k_f.t)) + (1-Q_f) (1 – \exp (-k_s.t))] \qquad (1)$$

where R (%) is the recovery at time t (min), R_{max} (%) the maximum attainable recovery of floatable material, Q_f the fraction of fast-floating species, k_f (1/min) the rate constant for fast-floating species, and k_s (1/min) the rate constant for slow-floating species.

The Kelsall parameters for both the valuables (4E) and the gangue are summarised in Table 1, the sum of squares (SSQ) values indicating the closeness of the fit. An interesting observation is firstly the fact that the optimum number of passes during preconditioning (i.e. providing maximum recovery) seem to be related to the feed grade, increasing from 10 on the rougher feed to between 20 and 30 on the recleaner feed. The rate constants of the fast floating fractions (k_f) were all high, suggesting that the samples responded well to preconditioning and with the exception of the rougher feed, improved compared to the baseline. The fast-floating fraction (Q_f) also increased with increasing feed grade of the samples (i.e. cleaner and recleaner feeds), suggesting that preconditioning by a reactor such as the Mach could have a positive impact in cleaner circuits, should the effect of preconditioning be carried through to the rest of the circuit. The slow-floating rate constants were also similar, or higher, after preconditioning, suggesting that the cleaning of particle surfaces has the most significant impact on the slow-floating fraction. The slow-floating nature of these particles could therefore be related more to inhibiting surface coatings than to incomplete liberation. Most significantly, the final recoveries (R_{max}) improved dramatically in all cases, suggesting a significant enhancement of floatability due to either surface cleaning or additional liberation, or some combination of the two.

Considering the results for the gangue, it appears that the predicted final mass pull (as approximated by R_{max}) for the cyclone overflow sample was decreased significantly from the baseline, as was that of the recleaner feed, and to a lesser extent that of the cleaner feed. It would be expected that the fast-floating fraction Q_f would be reduced by increasing preconditioning as species that could activate the gangue would be increasingly be removed from the surfaces. This was indeed observed for the cyclone overflow but not the cleaner or recleaner feeds. The results for the fast and slow floating rate constants are also somewhat difficult to decouple or explain; there does seem to be a trend for instance towards increasing of the rate of the slow-floating component. Of more significance though is the modelled final concentrate grades, calculated from the PGM recoveries and the mass pulls as predicted by the model, increasing by 61, 45 and 65% respectively for the rougher, the cleaner feed and the recleaner feed. Coupled with the significantly increased recoveries in each of these stages, it suggests that downstream circuit capacity could be reduced by the application of the reactor at one or more positions in the flowsheet. More work needs to be done to establish the reasons for the observed behaviour and to what extent the effect would be carried through.

Table 1: Kinetic flotation parameters of the valuable species (4E) and gangue. Zero passes represent the baseline conditions, running the feed through the 10 L Denver cell only.

Sample	**Rougher feed**		**Cleaner feed**		**Recleaner Feed**	
Head (g/t)	**0.7**		**2.2**		**10.6**	
Passes	**0**	**10**	**0**	**15**	**0**	**30**
Sum squares	1.55	0.44	1.44	1.64	0.01	0.01
Rmax	53.7	66.2	46.6	67.1	57.5	75.2
% increase	-	**23**	**-**	**44**	**-**	**31**
Q_f	0.35	0.26	0.31	0.34	0.34	0.53
K_f	1.35	1.16	1.76	2.13	1.34	1.41
K_s	0.07	0.09	0.15	0.13	0.08	0.13
Gangue						
SSQ	0.035	0.003	0.006	0	0.132	0.306
Rmax	20.3	15.6	9.9	9.8	29.5	23.4
Q_f	0.023	0.012	0.039	0.045	0.03	0.057
K_f	4.66	4.56	0.53	1.78	2.21	1.49
K_s	0.012	0.014	0.049	0.056	0.023	0.065
Grade at Rmax	1.85	2.97	10.36	15.06	20.66	34.06
% improvement	**-**	**61**	**-**	**45**	**-**	**65**

Commercial application

Following the successful demonstration of the impact of the Mach HSCD on PGM tailings samples in the Mintek laboratories on a variety of rougher, cleaner and recleaner applications, there are currently two Tailings Scavenger Plants in operation treating current arising PGM tailings in the the western limb of the Bushveld Complex. Both plants have a relatively high capacity with volumetric flowrates ranging between 1200 and 1500 m3/h on the roughing circuits. The plants treat a mixture of Merensky and UG2 ore, ranging from a 50:50 blend to 67% Merensky. Both plants have feed PSDs in the order of 65% passing 75 microns, one of them employing a stirred mill regrind to a P80 of 20 microns on the cleaner feed and a P80 of 5 microns on the recleaner feed.

The results of earlier tests on the feed to another PGM tailings concentrator were reported by Singh (2016), indicating that the effect of the reactors in a rougher application, where the blowers were offline, was most visible in the first cell and dissipated, as would be expected, further down the bank. This was evident in a bubble size distribution which was significantly finer than what was observed on the conventional mechanical cells that rely on the rotor-stator efficiencies for bubble generation only, and significantly increased gas holdups in the pulp, approaching 50% in certain cases. Roughing applications normally require fewer passes than cleaners, the optimum being reached for the current experimental set-up after something in the order of 10 passes. This is guided by testwork which typically shows improvement in selectivity with an increasing number of passes on the cleaning circuits. Depending on the application, power requirements for a full installation is in the order of 5 to 10 kWh/t only, which is attractive when viewed against the overall circuit recovery improvements which typically is in the order of 5% or more. This thus builds a strong business case for an HSCD such as the Mach when compared to other process routes such as ultrafine grinding of rougher feed with stirred mills, which can consume more than 40 kWh/t of energy, coupled with a high capital and operating cost for the milling equipment. Ultimately this consideration is of course mainly dependent on the mineralogy and texture of the feed sample, but it does offer a potentially cheaper option to achieve a considerable gain in recovery at a comparatively small outlay of capital and operating cost.

Another key feature of the Mach reactor is a high availability, inspections being conducted only on planned plant shuts, and its lifespan. Whilst HSCDs are generally regarded as high maintenance items - some requiring change-out of wear parts on a monthly basis – one of the tailings operations that uses the Mach has not required maintenance for the past two years with inspections revealing little to no wear on the internal components. Capital cost for a full commercial installation of 1200 to 1500 m3/h is in the order of USD 400k for pumps, pipelines and platforms. Capital payback for the installation was estimated to have been within 3 months of commissioning for both the PGM plants, where strong positive shifts in the grade-recovery curves are evident.

CONCLUSIONS

The efficient recovery of fine or oxidised platinum group mineral particles poses a significant challenge to flotation operations and a broad diversity of research investigations have been undertaken over the years in order to enhance metallurgical performance. This paper described the initial results of a comprehensive test campaign to better understand the impact of the various mechanisms that are believed to play a dominant role in the significantly enhanced efficiencies of PGM minerals from various stages of a tailings treatment plant.

The rougher feed (cyclone overflow) sample clearly demonstrated the benefit of the intensive inter-particle attritioning, improving the selectivity of PGM recovery especially during the early stages of flotation. Importantly, the final modelled recoveries (R_{max}) of PGMs improved dramatically in all cases, suggesting a significant improvement in floatability due to either surface cleaning or additional liberation, or some combination of the two. For the rougher feed, the final recovery was enhanced by more than 12% at a slight improvement in concentrate grade. Similarly, the cleaner feed recovery was improved by a significant 20% compared to the baseline, accompanied by a grade increase of 3 g/t. The results on the recleaner feed were equally promising, improving recoveries by nearly 18% at the expense of only a slight drop in the final concentrate grade. The kinetic data also indicated that the fast-floating fraction (Q_f) increased with increasing feed grade (i.e. cleaner and recleaner feeds), suggesting that the Mach could have a positive impact in cleaner circuits. The slow-floating rate constants were also similar, or higher, after preconditioning.

An interesting initial observation is the fact that the optimum number of passes of the feed slurry through the Mach reactor appears to be related to the head grade, ranging from 10 for the rougher feed at 0.7 g/t to around 20 to 30 for the recleaner feed at 11 g/t. Further investigations will be conducted in order to confirm and understand the reasons for this. Similarly, the cause for the recovery of the rougher feed to decrease after 10 passes, although still better than that of the baseline (at zero passes), needs to be understood. At this stage it is hypothesised that it could be to the increasing generation of slimes which would adsorb onto valuable mineral surfaces and render them increasingly less hydrophobic. One of the solutions would be the addition of dispersant during preconditioning, and preliminary results indicated this to be very promising.

The findings presented above, together with a data set of earlier tests on PGM ores, provide evidence of the significant positive impact that the cleaning of valuable particle surfaces has on the efficiency with which they are recovered, especially when in tailings form. Whilst it is a major challenge to assess the effect that possible additional liberation of valuables has on recovery, it is anticipated that further tests will elucidate the role and the relative impact of the increased gas holdup, and the mechanism of nucleation-aggregation, on flotation efficiency when the reactor is also employed for particle-bubble contacting during flotation. This will be complemented by a techno-economic analysis which would also consider the practicalities of implementing preconditioning for large-scale operations.

ACKNOWLEDGEMENTS
We gratefully acknowledge permission by Mintek management to publish the results of the testwork.

REFERENCES

Aldrich, C., Feng, D., 1999. Effect of ultrasonic preconditioning of pulp on the flotation of sulphide ores. Minerals Engineering, 12 (6), 701-707.

Bulatovic, S.M., Salter, R.S., 1989. High Intensity Conditioning: A New Approach to Improve Flotation of Mineral Slimes. Conference of Metallurgists, Halifax, Canada, pp. 182–197.

Calgaroto, S., Azevedo, A., Rubio, J., 2016. Separation of amine-insoluble species by flotation with nano and microbubbles. Minerals Engineering, 89, 24-29.

Changgen, L., Bahr, A., 1992. Flotation of copper ore in a pneumatic flotation cell. Minerals and Metallurgical Proc, 9, 7–12.

Chen, G., Grano, S., Sobieraj, J., Ralston, J., 1999. The effect of high intensity conditioning on the flotation of a nickel ore. Part 2: Mechanisms. Minerals Engineering, 12 (1), pp. 1359-1373.

Dickinson, J.E., Galvin, K.P., 2014. Fluidized bed desliming in fine particle flotation Part I. Chemical Engineering Science. Volume 108, 28 April 2014, Pages 283–298

Hu, H., Finch, J.A., Zhou, Z., Xu, Z., 1998. Numerical and experimental study of a hydrodynamic cavitation tube. Metallurgical and Materials Transactions B, 29(4), 911–917.

Martínez-Gómez, V., Pérez-Garibay, R., Rubio, J., 2013. Factors involving the solids-carrying flotation capacity of microbubbles. Minerals Engineering 53 (2013) 160–166

Nesset, J.E., Hernandez-Aguilar, J.R., Acuna, C., Gomez, C.O., Finch, J. A., 2006. Some gas dispersion characteristics of mechanical flotation machines. Minerals Engineering, 19(6), 807–815.

Oliveira, H., Azevedo, A., Rubio, J., 2017. Nanobubbles generation in a high-rate hydrodynamic cavitation tube. Minerals Engineering, in press. Nov. 2017.

Qi, B.C. and Aldrich, C., 2002. Effect of ultrasonic treatment on zinc removal from hydroxide precipitates by dissolved air flotation. Minerals Engineering, 15(12), 1105-1111.

Rule, C.M. and Anyimadu, A.K., 2007. Flotation cell technology and circuit design - an Anglo Platinum perspective. Journal of the South African Institute of Mining and Metallurgy, 107(10), 615.
Singh, A., 2016. Enhanced flotation of platinum mineral fines through feed cavitation: 'Bringing the mountain to Mohamed'. IMPC 2016: XXVIII International Mineral Processing Congress Proceedings, Quebec City.
Sobhy, A., & Tao, D., 2013. Nanobubble column flotation of fine coal particles and associated fundamentals. International Journal of Mineral Processing, 124, 109-116.
Subrahmanyam, T.V., Forssberg, E.S., 1990. Fine particle processing: shear flocculation and carrier flotation – a review. International Journal of Mineral Processing 30, 265–286.
Tabosa, E., Rubio, J., 2010. Flotation of copper sulphides assisted by high intensity conditioning (HIC) and concentrate recirculation. Minerals Engineering 23, 1198–1206.
Tao, D., 2005. Role of bubble size in flotation of coarse and fine particles – a review. Separation Science and Technology, 39 (4) 741-760.
Yoon, R.H., Luttrell, G.H., Adel, G.T., Mankosa, M.J., 1989. Recent advances in fine coal flotation. Advances in Coal and Mineral Processing Using Flotation, 211–218.
Zhou, Z.A., Xu, Z., Finch, J.A., 1995. Fundamental study of cavitation in flotation. Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO (United States).