Minerals Engineering 137 (2019) 133–139

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Improved flotation of PGM tailings with a high-shear hydrodynamic cavitation device

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ARTICLE INFO

Keywords:
Hydrodynamic cavitation
Flotation mechanisms
Gas holdup
Nano-bubble
Micro-bubble
Kinetic parameters

ABSTRACT

Fine liberated valuable particles are often lost to flotation tailings due to inefficient collection by air bubbles, and passivation of their surfaces by oxidation products and slimes when reclaimed from tailings dams. Extensive research covering a diverse range of technologies has been undertaken over the years to find feasible solutions to this problem, with only relatively minor success at an operations scale. A more recent and practical prospect which has already found application in the mining industry is the use of hydrodynamic cavitation devices (HCDs), causing the nucleation of ultrafine (nano) bubbles (NBs) on the surfaces of fine valuable particles, thus aiding their agglomeration and subsequent recovery by micro-bubbles (MBs) and normal sized (macro) flotation bubbles. This paper details investigations that have been undertaken on the Mach HCD reactor, using rougher, cleaner and recleaner feed samples sourced from a UG2 Platinum Group Metal (PGM) tailings operation. The results suggest that the formation of NBs and MMBs, together with enhanced cleaning of particle surfaces, were the dominant mechanisms. This not only lead to activation of valuable mineral surfaces but also depressed the recovery of gangue. The flotation kinetics were analysed using the modified Kelsall model, showing significant improvements in the maximum (fitted) recovery Rmax, together with a reduction in mass pull, for the optimum number of passes of the various feed samples through the reactor. The contributions to the increased recovery due to additional liberation of PGMs from the chromite grains and the increased gas holdup, are being investigated further.

1. Introduction

It is well established through research and practical experience that the recovery of fine and ultrafine valuable mineral particles, the latter typically less than 10 µm in size, by flotation is a challenge (Yoon et al., 1989; Miettinen et al., 2010). Due to their low mass and inertia, the collision efficiency with air bubbles is low due to the inability of such particles to penetrate the liquid streamlines around bubbles. Hence the probability of contact is often regarded as the rate-determining step in flotation of ultrafine particles, and this often results in a significant mass pull due to the prolonged flotation time that is required to effect acceptable recoveries in flotation circuits.

The challenge of fines and ultrafines flotation has in recent years become more pronounced due to the increased use of fine and ultrafine grinding (UFG) to achieve better liberation of valuable minerals, especially in lower grade or complex ores. Rule and Anyimadu (2007) for instance demonstrated that after addressing liberation issues with UFG in inert stirred milling, an alarmingly high proportion of < 10 µm and particularly < 5 µm fully liberated Platinum Group Minerals (PGMs) were being lost to tailings. They commented that this problem was unlikely to be solved by introducing more power into conventional flotation cells and that different flotation technology would be needed to overcome the problem. 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 ensure adequate particle-bubble contact under such circumstances. The flotation of tailings material in retreatment operations makes 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 and slimes. However, as Pease et al. (2006) point out, the appropriate design of flotation circuits to account for a distribution of particle sizes, and the use of inert grinding to create clean particle surfaces, have several advantages as far as reagent consumption and fines recovery are concerned.

Over the years, various approaches to improve flotation of especially fines have been investigated. These include sonication of the feed

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https://doi.org/10.1016/j.mineng.2019.04.005
Received 28 September 2018; Received in revised form 4 March 2019; Accepted 3 April 2019

to clean particle surfaces (Aldrich and Feng, 1999;), high intensity conditioning (Bulatovic and Salter, 1989; Chen et al., 1999; Tabosa and Rubio, 2010), seed or carrier flotation (Subrahmanyam and Forssberg, 1990; Tabosa and Rubio, 2010), such as spiking the pulp with concentrate to promote the formation of agglomerates that are easier to recover by air bubbles, the use of dissolved air flotation to form microbubbles (MBs) (Rodrigues and Rubio, 2007; Englert et al., 2009; Martínez-Gómez et al., 2013), and electrochemical approaches such as changing the redox potential (Eh) to promote the formation of dixanthogen, dissolution of oxidation products by lowering the pH, activation by sulphidisation, or the use of alternative collectors to float oxides and hydroxides.

Another, more recent, development for the efficient recovery of fines and ultrafines is the use of nano-bubbles (NBs), typically a few hundred nanometer in size, that are formed when the instantaneous pressure of a saturated liquid falls below its vapour pressure as it passes through a constriction and the velocity increases (Hu et al., 1998). In a slurry, the hydrodynamic cavitation causes the nucleation of NBs on particle surfaces, this being favoured on hydrophobic and rough particle surfaces which could also have minute quantities of gas trapped in crevices on the surface as they exit a milling circuit. These NBs on the particles are characterised by a high stability, great longevity and rapid attachment to hydrophobic surfaces (Etchepare et al., 2017). For instance, in a study involving the formation of NBs in a 2-phase system with a centrifugal multiphase pump (CMP), it has been shown that they are resistant to the shearing of pump impellers during successive bubble generation cycles. Their concentration increased with increasing pressure (the maximum being reached at 5 bar) and with increasing generation cycles, a plateau being reached after 29 cycles (Etchepare et al., 2017). Due to these properties, the NBs thus also tend to function as a 'secondary collector' (Huang et al., 2016) which can be stabilised by the addition of frother to the slurry and can also lead to reduced consumption of reagents (Sobhy and Tao, 2013). These NBs on their own however cannot provide sufficient buoyancy to float mineral particles and hence the presence of MBs (typically 30–70 μm in diameter) and flotation size (macro) bubbles, typically in the range of 600–2 mm, are still required.

It is therefore suggested that the NBs and MBs be introduced into flotation cells to complement, rather than replace, flotation size bubbles (Tao, 2005; Tao et al., 2006; Nesset et al., 2006). Since ageing of the NBs as well as macro bubbles is detrimental to particle-bubble attachment, optimum flotation conditions are obtained under conditions in which the two are co-generated (Huang et al., 2016). The mechanism is depicted graphically in Fig. 1, involving the nucleation of NBs on the surfaces of fine hydrophobic particles. Intensive mixing of the slurry would lead to the formation of aggregates of hydrophobic fines through a bubble bridging mechanism (Tao et al., 2006; Singh, 2016). The final step in the process is the presentation of an effectively larger and more homogeneously hydrophobic particle to a macro-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.

The use of NB/MBs to more effectively float fines and ultra-fines has already found commercial application in the form of hydrodynamic cavitation devices (HCDs) such as the Eriez CavTube (Oliveira et al., 2018) and the GoldOre Mach reactor (Singh, 2016). These devices typically consist of an array of venturi nozzles in series or a multitude of parallel, restricted apertures in which intimate contact is achieved between the fine particles and the distribution of very fine bubbles that are formed due to cavitation and the conditions of high shear. This results in a hydrodynamic environment in the pulp zone which contrasts markedly with that observed with conventionally aerated mechanical flotation cells; for example, the significantly increased gas holdup that develops within the pulp at the high gas fluxes and very fine bubbles is also believed to form a sort of 'safety net' in which particles that detach could readily re-attach to bubbles (Dickinson and Galvin, 2014).

1.1. Complementary mechanisms

Relatively little information is currently available regarding the various mechanisms that affect the efficiency of HCDs in slurry systems under different operating conditions. The results of earlier exploratory work on the Mach reactor at Mintek on a variety of ores, together with the findings of published literature on hydrodynamics and flotation of fines, however suggest that the mechanism of bubble nucleation and aggregation is responsible predominantly for increased flotation kinetics but is complemented by at least three other, distinct mechanisms. The relative impact of each of these would depend on the specific type of ore, its grind and liberation, and its condition as far as surface passivation is concerned.

1.1.1. Surface cleaning

HCDs impart significantly higher shear and energy dissipation rates to the feed compared to conventional mechanical flotation cells. They can thus be used as effective inter-particle attritioners by recirculation of feed slurry through the device, aiding in the removal of oxidised layers and slime coatings from the surfaces of valuable mineral particles. This mechanism is believed to be a major contributor to the enhanced flotation kinetics and recoveries that have consistently been observed when using the Mach reactor on PGM tailings samples, as will be discussed further in this paper. Another, equally important, observation was the significant decrease in mass pull achieved by the preconditioning of run-of-mine PGM samples. Although the changed hydrodynamic conditions in the pulp presumably was the main contributor to a decreased degree of entrainment under these circumstances, the deactivation of gangue minerals due to the removal of hydrophobic rimming by talc and other species also needs to be considered.

1.1.2. Increased liberation

Due to the repeated and intensive inter-particle interaction that occurs when flotation feed slurry is circulated through the reactor, it is likely that the attrition could increase the liberation of fine valuable

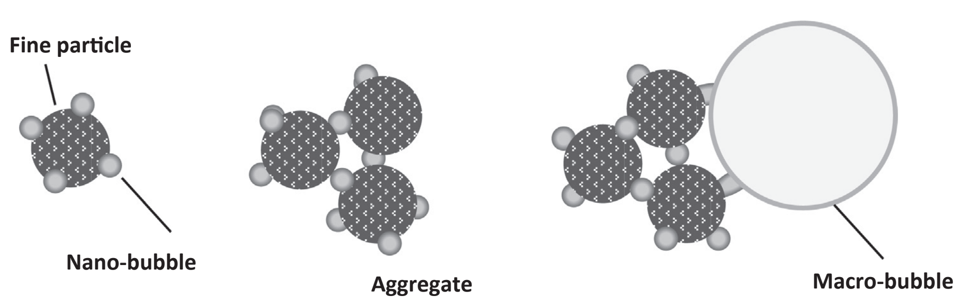

Fig. 1. Mechanism: Nucleation of nano-bubbles on fine particles, followed by agglomeration of the hydrophobic fines and subsequent collection by flotation size (macro) bubbles (not to scale).

particles from the gangue, such as 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 with the gangue coating being worn away with each successive pass. Earlier tests in which the particle size distribution before and after preconditioning was compared, indicated an increased quantity of slimes being generated, lending credibility to such a proposed mechanism.

1.1.3. 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 a significantly increased bubble flux and hence improved flotation kinetics. An added effect is the increased gas holdup in the pulp caused by the reduced bubble size, levels of around 50% having been measured compared to the ~10 to 15% that is typical of conventional mechanically agitated cells. The high gas holdup corresponds well with those measured by Dickinson and Galvin (2014) in the bubbly foam regime of the reflux flotation cell and creates conditions in which entrainment is apparently reduced due to the increased proportion of finer bubbles with a reduced rise velocity.

2. Experimental

2.1. Ore samples

Three samples from a UG2 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 and kept in slurry form for the duration of the testwork. A total of approximately 10 kg of each was sub-sampled for head assays, showing good reproducibility and averaging 4E (i.e. combined Pt, Pd, Rh and Au) grades 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 Fig. 2, the rougher feed material being relatively coarse at 56% passing 75 µm. Both the cleaner and recleaner samples were however very fine at more than 80% passing 25 µm and thus, despite their higher feed grades and particles being relatively well liberated, proved difficult to float under conventional conditions and achieve reasonable flotation kinetics.

2.2. Mach reactor

A schematic representation of the Mach reactor is shown in Fig. 3: a mixing nozzle feeds into high-speed cavitating nozzles which in turn jet into a collection nozzle before the slurry exits the reactor. Air is injected between each nozzle at a pressure of around 5 bar. This design enhances

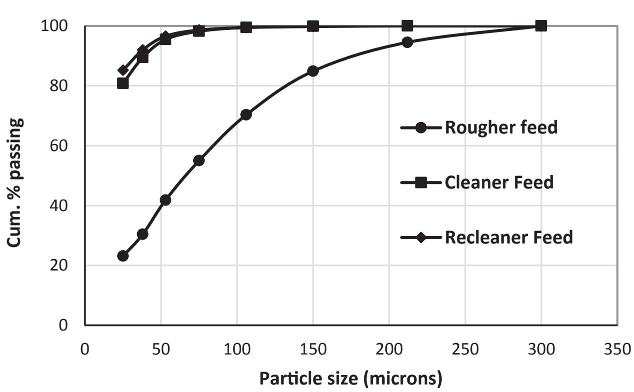

Fig. 2. Particle size distributions for the three UG2 tailings operations samples.

cavitation in the high-speed nozzles as well as the initial aggregation of hydrophobic fine particles in the collection nozzle. The latter, which incorporates features of a plunging jet, also generates micro- and macro-bubbles which attach to particle-bubble aggregates to complete the collection process and provide for a higher rate of flotation in a conventional flotation cell. In addition, the reduced bubble size translates to a significantly higher bubble flux than in conventional machines which, together with higher shear and energy dissipation rates, leads to better flotation of fines. Considerations for selecting this reactor for the test programme included ease of operation and reduced downtime due to blockages and wear, as well as its modularity and the fact that it could be scaled quite easily to enable investigations at both a laboratory and pilot scale.

2.3. Test procedure

The test programme entailed firstly a conventional batch rougher rate flotation test that was performed on each slurry sample in a 10 L laboratory Denver cell to set the respective baselines. The slurry was conditioned for 5 min (SIBX at 200 g/t, KU433 depressant 100 g/t, XP200 frother 40 g/t) before flotation commenced at a superficial gas velocity (Jg) of 0.6 cm/s and concentrates being collected after 1, 3, 7, 14 and 30 min of flotation. In subsequent tests (Fig. 4), the feed sample was preconditioned in the Mach reactor for a certain number of passes by recirculation for the required time via an agitated feed tank, the slurry flowrate being maintained at around 45 L/min and air into the reactor at 17 L/min. After preconditioning, the required volume of preconditioned slurry was diverted to the 10 L Denver cell and conditioned with reagents in the same manner as with the base case. As such, a comparison could be made with the baseline conditions where no surface cleaning or hydrodynamic cavitation occurred. Further tests will be aimed at understanding the effect of the changed pulp hydrodynamics more clearly, and the way in which the froth phase contributes to reducing entrainment.

3. Results and discussion

3.1. Rougher

Summarised flotation results for the cyclone overflow (rougher feed) sample are presented in Fig. 5. The kinetic response for the various tests was quite consistent, the early gains that were made in each case carrying through to the total flotation time of 30 min, 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 min was 49% with a corresponding 4E grade of 4.9 g/t, representing an upgrade ratio (UR) of around 7. After 5 passes through the reactor, the recovery increased to 52% at an overall grade of 6.5 g/t (UR of 9), indicating an increased rejection of the gangue as the PGMs also became progressively more floatable. As alluded to earlier, the reduced gangue recovery in this case was presumably due to a combination of the deactivation of gangue surfaces and changed hydrodynamics in the pulp and froth phases. A 10-pass preconditioning further improved recovery to 63%, also hiking the 4E grade to 7 g/t.

Whilst further increasing the preconditioning still enhanced the recovery of PGM compared to the baseline, it was not to the same extent as 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 final concentrate grade of around 5 g/t. The reason for this is not clear at this stage; on the one hand it may be simply due to experimental error as a result of for instance the difficulty in transferring an exact volume of slurry into the Denver cell from the rig, and changes in gas holdup with increased conditioning time. Another train of thought, seemingly consistent with the results of the cleaner and recleaner feeds, is that the

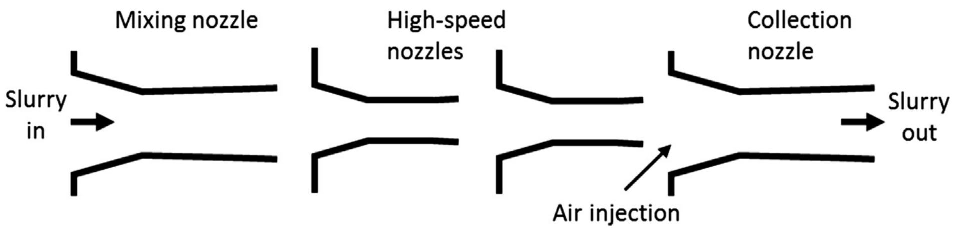

Fig. 3. Schematic of Mach reactor.

sample still contained a significant amount of easy-sliming gangue that broke down with successive passes through the reactor and thus negated the increased floatability. The addition of dispersant to the reactor feed for instance yielded positive results in terms of recovery.

3.2. Cleaner

The pronounced effect of preconditioning of the cleaner feed through the Mach HCD on the flotation kinetics, grade-recovery relationships and the upgrade ratio of the PGM tailings is further confirmed in Fig. 6 for the cleaner feed. Although the results are clustered fairly tightly, it appears that the optimum kinetics and final 4E recovery in this case occurred after around 15 passes of the feed slurry through the reactor. 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 min in the mechanical flotation cell, a concentrate of 16 g/t and 46% recovery was attained for the baseline conditions, representing a UR 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 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 was observed for the rougher floats, longer pre-conditioning seemingly resulted in a slightly decreased recovery; the exact cause of this not yet clear. The pulp temperature also increases with successive passes through the reactor, and whilst this could enhance kinetics, the behaviour of reagents could be adversely affected.

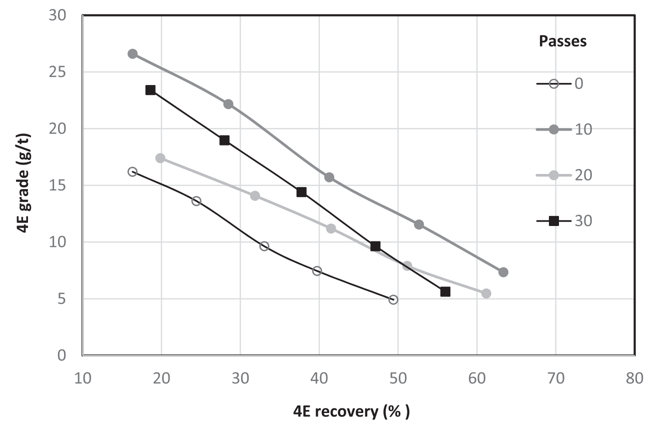

Fig. 5. Grade-recovery results for the rougher feed.

3.3. Recleaner

Fig. 7 shows the grade-recovery and kinetic relationships for the recleaner feed sample, again demonstrating the significant impact of preconditioning in a high-shear environment on the flotation efficiency. As was the case for the rougher and cleaner feeds, the baseline test (at a

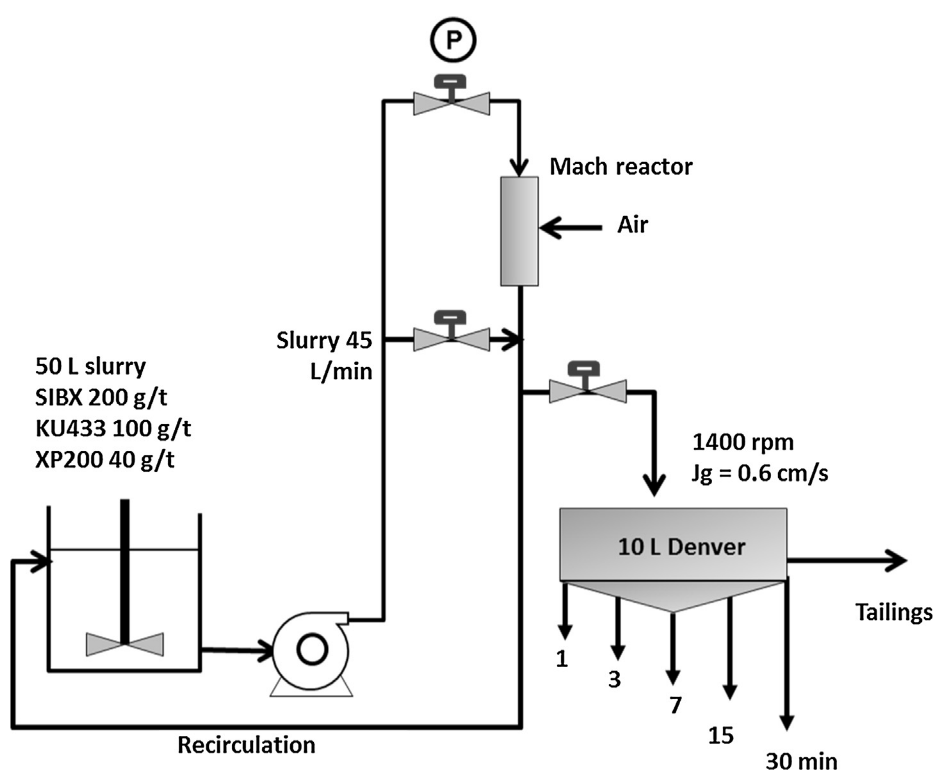

Fig. 4. Experimental setup for flotation tests.

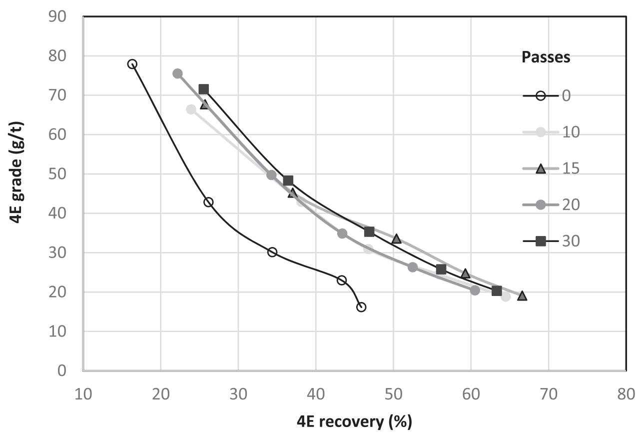

Fig. 6. Grade-recovery results for the cleaner feed.

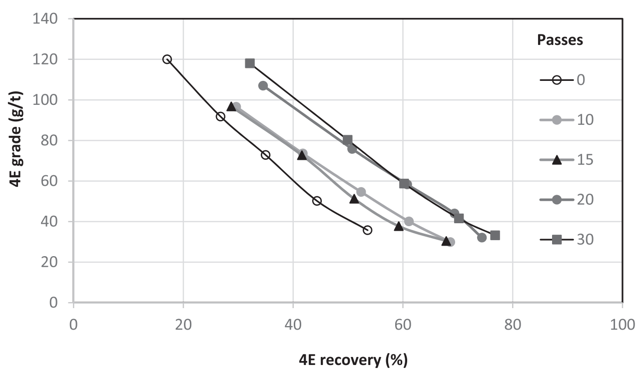

Fig. 7. Grade-recovery results for the recleaner feed.

total residence time of 30 min) 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 (to 67%) with the overall concentrate grade slightly reduced to 31 g/t due to a higher mass pull. In accordance with the previous tests, the significantly increased PGM kinetics after preconditioning carried through systematically to the 30 min of total flotation time. Whilst the final concentrate grades again remained static, sharp increases in the final recoveries were achieved, lifting the 54% of the baseline to 77% after 20 to 30 passes through the reactor. In this case, as was to be expected from our initial hypothesis, increased preconditioning systematically increased the performance across the full range of experimental conditions. Since the liberation of valuable mineral (PGMs) in the fine recleaner feed would be expected to be markedly higher than in the much coarser rougher feed, it suggests that the higher ratio of valuable mineral allowed for a greater cumulative effect of nano-bubbles and thus better flotation response. This is an initial observation based on a limited set of exploratory results but deemed to be a key factor that needs to be explored in more detail as it could provide fundamental insight into the mechanisms that drive hydrodynamic cavitation in complex three phase systems.

3.4. Kinetic parameters

Flotation kinetics data of the baseline and optimum Mach preconditioning conditions were analysed by means of the modified Kelsall model, using an 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 very small) were modelled. The model characterises the mineral species into two rate classes corresponding to slow and fast floating components, and is of the form:

Table 1
Kinetic flotation parameters of the valuable species (4E) and gangue. Zero passes represent the baseline conditions.

	Rougher feed		Cleaner feed		Recleaner Feed	
4E head (g/t)	0.69		2.22		10.6	
Passes	0	10	0	15	0	30
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						
Rmax	20.3	15.6	9.9	9.8	29.5	23.4
Q_f	0.02	0.01	0.04	0.045	0.03	0.06
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

$$R = R_{max}[Q_f(1 - \exp(-K_f \cdot t)) + (1 - Q_f)(1 - \exp(-K_s \cdot t))] \quad (1)$$

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 average rate constant for fast-floating species, and k_s (1/min) the average rate constant for slow-floating species.

The Kelsall parameters for both the valuables (4E) and the gangue under the optimum conditions are summarised in Table 1. The rate constants of the fast-floating fractions (k_f) were all high, suggesting that the samples responded well to preconditioning and except for 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 predicted mass pulls, 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 on a commercial scale where fewer passes of slurry would be possible as a result of the higher volumetric flowrates of slurry.

3.5. Commercial application

Following the successful demonstration of the impact of the Mach HCD on PGM tailings samples at Mintek on a variety of rougher, cleaner and recleaner applications, there are currently two Tailings Scavenger Plants in operation treating PGM UG2 tailings from current arisings in the western limb of the Bushveld Complex. Both plants have a relatively high capacity with volumetric flowrates ranging between 1200 and 1500 m^3/h on the roughing circuits. The plants treat a mixture of Merensky and UG2 ore, ranging from a 50:50 blend to 67% Merensky. Feed particle size distributions are in the order of 65% passing 75 µm for both plants, one plant employing a stirred mill regrind to a P80 of 20 µm on the cleaner feed and a P80 of 5 µm 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 some 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 5–10 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 HCD 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 its high availability, inspections being conducted only on planned plant shuts, and its lifespan. Whilst HCDs are generally regarded as high maintenance items - some requiring change-out of wear parts on a monthly interval – 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 1200–1500 m^3/h is in the order of USD 400 k 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.

4. Conclusions

The efficient recovery of very fine or oxidised valuable mineral particles poses a significant challenge to flotation operations and a diversity of research investigations have been undertaken over the years to enhance metallurgical performance. This paper described the initial results of a comprehensive test campaign using a hydrodynamic cavitation device (HCD), to better understand the impact of the various mechanisms that are believed to play a 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 attrition as the feed slurry passes through the Mach reactor, 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 a 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 reactor could have a positive impact in cleaner circuits. The slow-floating rate constants were also similar, or higher, after preconditioning.

An interesting though as yet unsubstantiated observation is that the optimum number of passes of the feed slurry through the Mach reactor seems to be related to the head grade, in this case increasing as the head grade increased. Further investigations will be conducted to verify this. Similarly, the cause for the recovery of the rougher feed to decrease after more than 10 passes, although still better than that of the baseline (at zero passes), needs to be understood via reproducibility tests. At this stage it is hypothesised that it could be to the increasing generation of slimes which would render valuable minerals less floatable. Preliminary results for instance indicated the addition of dispersant during preconditioning to be 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 the form of reclaimed tailings. Whilst it is a major challenge to clearly decouple the effect that possible additional liberation of valuables has on recovery, it is anticipated that further tests will elucidate the relative impact of the increased gas holdup, and the mechanism of nucleation-aggregation, on flotation efficiency.

Acknowledgements

The authors acknowledge financial support of Mintek for the experimental work and the approval of Mintek management to publish the results.

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