The Feasibility of Ferro-alloy fines Recovery by using Centrifugal Separator Technology[†]

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Abstract

The effect of an increase in gravitational force on the separation of a binary (different densities) mixture of particles in a centrifugal separator is investigated. An algorithm calculates the effect an increase in gravity has on improving separation using established particulate fluidised bed models. These results are compared to separation data generated by a continuous centrifugal separator.

Introduction

The development of a number of batch and continuous centrifugal separators over the past twenty years has resulted in the widespread use of these instruments in the gold mining industry [1]. Formerly, the industry was faced with the problem of removing free gold particles that entered the circuit of a typical gold plant, causing increased gold hold-up, spiking and a general drop-off in efficient recovery. There are many examples of gold plants that have solved this problem by the introduction of a centrifugal separator in a bleed stream of the mill product circuit, effectively scalping the free gold particles before they enter the leach train. Base metal plants that use flotation to recover copper, zinc and lead concentrate tend to lose trace amounts of gold that may enter the circuit if present in the mine ore body. The heavier gold particles tend to migrate to the tailings of the flotation cells and are lost, thus eliminating a potential source of revenue for the mining company. There are a number of examples where the use of centrifugal technology effectively improved gold recovery [2]. In one case, the improvement was so marked that the status of the plant changed from that of a base metal to that of a zinc/gold plant [3].

More recent publications have suggested that centrifugal technology could also be used in the recovery of less valuable synthesised minerals [4], i.e. ferro-

chrome from crushed slag dump material. The production of ferro-chrome by reduction in a smelter tends to generate a mixed stratum of matt and slag at the interface. The amount of ferro-chrome present in this stratum is sufficient to warrant processing and recovery. This challenge is common in the ferro-alloy industry and is topical at present. As comminution of this stratum results in total ferro-chrome particle liberation, the removal from the slag particles, which are approximately half the density, should be achievable by gravity/hindered settling techniques. Recent successes in this regard have shown that by gravity separation, most of the ferro-chrome particles larger than 200 microns are easily removed [5]. The same cannot be said for the fully liberated, sub-200-micron, ferro-chrome particles, which is where the bulk of the post-comminution ferro-chrome particles are found. **Figure 1** gives the mass percentage per size fraction of ferro-chrome in a typical 750-g grab sample taken from the tailings of a Titaco (slag dump material) processing plant. We observe that some 60% of the ferro-chrome particles are in the sub-200-micron range and have not been removed by conventional gravity separation, i.e. jigs. It is also apparent that approximately two percent of the entire sample is ferro-chrome. At an approximate market value of 1000 USD per tonne of ferro-chrome, this represents a calculable loss to the plant. It is reported that a similar loss occurs with other ferro-alloy producing plants.

In this paper it is assumed that the hindered settling zone found in a centrifugal separator is comparable to a fluidised bed approaching steady state. Our intention is to simulate the behaviour of such a bed

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Fig. 1 Mass of Ferro-Chrome in the tailings of a Titaco processing plant

using typical fluidised bed mathematical models, accommodating the increase in gravity that would be the norm in a centrifugal separator. The density and general physical properties of chromium oxide (Cr_2O_3), with an RD of approximately 7.0, was deemed to be very similar to that of the majority of ferro-alloys and therefore, in the theoretical study and test work, this material was considered to be the valuable/recoverable material. Metal/silica oxides with RDs of approximately 3.0 were considered to be the gangue material. An algorithm was employed to simulate the fluidised mixed bed of these two species that demonstrably showed the presence of three zones: an upper zone, where only the lower density species is present (metal/silica oxides); a middle zone comprising a mixture of both species; and a lower zone containing only the higher density species (ferro-alloy). Having established this simulation in the form of a software package, the effect of an alteration in gravity could be observed. These results were then compared to those achieved by a centrifugal separator in chromium-oxide recovery duty.

Theory

The failure of gravity equipment to efficiently recover the sub-200-micron ferro-chrome particles by hindered settling can be attributed to two phenomena. The first is that the system is clearly in Stokes-laminar-settling regime. Calculation of the terminal velocity Reynolds numbers in water of the sub-200-micron ferro-chrome particles proves this. These can be estimated using a simple terminal velocity relationship proposed by Hartman *et al* [6], and are all less

than 14 for the sub-200-micron range. Classification under normal gravity will therefore be inefficient. The second challenge is the blinding effect of the free settling ratio of the ferro-chrome to slag particles. The presence of a skew distribution of particles results in the probability that the hydrodynamic characteristics of the sub-200-micron ferro-chrome particles are likely to be emulated by larger less dense slag particles. Assuming Stokes regime and that the ferro-chrome/slag particles are spherical, it may be calculated that a slag particle in the 16 to 320-micron range will emulate the terminal velocity of a ferro-chrome particle in the 10 to 200-micron range.

Common knowledge holds that by increasing the gravity forces (increasing terminal velocity of the particles) on a hindered settling system, the first challenge, i.e. the presence of Stokes settling regime, can be overcome. This can be achieved by a centrifugal-gravity separator. The blinding effect, as understood from the perspective of Stokes' or Newton's hindered settling equations, clearly shows that a sufficient increase in gravitational force will cause the hydrodynamics of a hindered settling system to change from the laminar settling regime to the turbulent, effectively altering the blinding ratio. It can be calculated that in the case of a switch from Stokes' to Newton's regime, the average ferro-chrome particle would now be blinded by a larger slag particle than was the case in the Stokes' regime. The removal of larger slag particles by means of screening after the application of conventional gravity separation (jigs) should lead to improved recoveries by subsequent treatment with high-gravity centrifugal separation. Examination of a centrifugal separator would indicate that the hindered settling zone is comparable to a fluidised bed approaching steady state, under severe gravity. **Figure 2** clearly shows how a mixture of particles of different

Fig. 2 Typical centrifugal separator mechanism

densities moves through a centrifugal separator, with the denser particles tending to move closer to the rotating wall while the less dense tend to migrate over the top of these particles under the influence of centrifugal forces. Fluidising water enters the separator through the rotating wall, effectively causing a fluidised bed at higher gravity.

Traditional fluidisation expansion models for particulate fluidisation correlate the voidage (e) of a system to the superficial fluid velocity (U) and the Galileo Number of the particles, which itself is closely related to terminal velocity (U_t).

These correlations are summed up in the Richardson and Zaki equation [7]:

$$U = U_t e^n \quad \text{Eq. 1}$$

where n is a function of the Galileo Numbers of the particles present.

The application of this model has traditionally been by means of the averaging [8], serial [9], or cell model [10] techniques. The model of Nesbitt and Petersen [11] has been shown to effectively predict the expansion of a fluidised bed of polysized spherical particles, and relies entirely on the serial model philosophy and an original technique for application.

The model of Nesbitt and Petersen [11]:

$$E_t = 1 + \int_{dp=s}^{dp=l} G(dp) \left(\frac{1 - e_{fws}}{1 - [U/F(dp)]^{1/n}} - 1 \right) d(dp) \quad \text{Eq. 2}$$

where $F(dp)$ is the terminal velocity function for the particle size range

$G(dp)$ is the function correlating particle size to bed mass fraction, and

s, l refer to the smallest and largest particle present, respectively (m).

In application, this model validates the assumption that a fluidised bed in an expanded state is a serial combination of the expansion of each particle size class. Each size class contributes to the overall extent of expansion to the same degree as it would demonstrate if isolated, with all other physical aspects remaining unchanged. The cell model was proposed by Patwardhan and Tien [10], where they show how each particle demands a certain volume around itself depending on its own physical properties and those of the fluid. This combination of the mass of particle and required void is said to act as a discrete finite element with a volume and density. An element located at the bottom will have the highest cell density of all elements in the bed. Cell density decreases with increased height in the bed, and the cell with the lowest density is found at the top. The stratification of

particles on the basis of size for a large particle size distribution was observed by Al-Dibouni and Garside [12]. No reference could be found in the literature effectively testing traditional fluidisation/bed expansion mathematical models in a gravity field other than that of $g = 9.81 \text{ m.s}^{-2}$. However, for the purposes of this study, the simulation of a change in gravity force was deemed to be achievable by altering the g term in the Galileo Number, for the purpose of determining the n value in Eq. 1 and the terminal velocity of each particle present. Assuming the models of Nesbitt and Petersen [11] and of Patwardhan and Tien [10] to be effective, it now becomes possible to define the vertical position of a discrete cell relative to the total height of the bed on the basis of its density. It has already been stated that the discrete element density decreases with bed height, and assuming perfect stratification, which is reasonable for a large particle size distribution [12], the density of a discrete element is a function of particle size distribution and particle density, both of which are well defined.

An algorithm was produced in the form of a computer program that simulated the separation of the binary mixture of particles with each species possessing two distinct particle size distributions. A schematic diagram of the algorithm is given in **Figure 3**. To calculate the mass of particles that would be present in the mixed (central) zone, it is necessary to establish its vertical boundaries. The steady-state position of the largest of the less dense particles (dp_{ll}) would make up the lower boundary, while the smallest of the more dense particles (dp_{2s}) would form the upper boundary of this mixed zone. At a given flow rate the voidage for the largest particles of the less dense species (dp_{ll}) is calculated and consequently the bulk density of the associated discrete finite element is attained. The same calculation is achieved for the smallest particle of the denser species (dp_{2s}). The density of the discrete finite element in each case was thus judged to be the boundary density for the lower and upper boundaries, respectively. Once these boundaries were set, the bulk density of the discrete finite element associated with every particle class of both species present was calculated. If it fell between the boundary limits, the associated particle was judged to be part of the mixed zone. The particle size distribution of each species had to be defined and this was achieved by examining typical raw data. The particle size distributions of the two species were considered to be of a continuous nature and hence spline routines were used to represent each. The spline routines developed were impor-

Fig. 3 The algorithm used to determine the mass of particles in the mixed (central) zone

tant for determining functions $F(dp)$ and $G(dp)$ for each species.

The calculation of the bulk density of each discrete finite element was achieved by using Eq. 3. Initially the voidage (e) is calculated by applying Eq. 1 discretely to every particle size class.

$$\rho_c = (1 - e)\rho_s + e\rho_f \quad \text{Eq. 3}$$

where ρ_c is the relative density of the discrete finite element

ρ_s is the intrinsic relative density of the solid particle

ρ_f is the relative density of the fluid.

Results and discussion

Figure 4a diagrammatically represents particles of both species on a mass basis that will migrate to the mixed zone – area between dotted lines – under a gravity force of one. The vertical component in the diagram refers to successive cell densities with the highest density cell being at the bottom and the lowest at the top. The simulation was then repeated at higher gravity forces, primarily to observe the influence this had on the mass of particles migrating to the mixed zone. **Figure 4b** shows the characteristic reduction in the mass of particles migrating to the mixed zone, observed for any increase in gravity. For all simulated gravity forces in excess of normal grav-

Fig. 4a shows the mixed bed under normal gravity

Fig. 4b is the identical system to **4a**, experiencing increased gravity.

ity, less mass migrated to the mixed zone. The fluidising medium used in the simulation was given the physical characteristics of water.

Certain parameters that would be present during centrifugal separation could not be brought into the simulation. An example is the mass pull of denser material that is an independent setting likely to have an influence on the efficiency of separation. An increase in this setting is likely to move the system away from steady-state fluidisation. The setting is normally presented as a “time duration” within a fixed time cycle for which the concentrate valve remains open, allowing denser material to leave the centrifugal separator. This oscillation effectively controls the changing ratio, at which the two species migrate through the centrifugal separator, relative to each other. In addition, the violent nature of the centrifugal phenomenon could well cause a greater degree of mixing than would be present in a steady-state fluidised bed experiencing a mild increase in gravity

force. **Figure 5** is a typical result developed by the simulator. It assumes the mass of particles present in the mixed zone at a gravity of one to be 100%, and effectively shows how a mixed fluidised bed experiencing an increase in gravitational forces results in a decrease in the mass of particles present in the mixed zone. It is notable that perfect separation is achieved relatively quickly at a gravitational force equivalent to an acceleration of 24.81 m.s^{-2} , and is an indication of the level of efficiency that could be achieved by a centrifugal separator.

From the results of test work carried out on a chromium oxide/silica oxide mix passed through a centrifugal separator, an improvement in separation with increase in gravity was clearly observed.

Table 1 gives the percentage of chromium oxide in the feed to migrate to the concentrate versus gravity. The gravity acceleration was calculated from the revolutions per minute of the centrifugal separator.

Fig. 5 % Mass of mixed particles

Table 1 Percentage chrome oxide fed to a Knelson concentrator (CVD) reporting to concentrate

Generated increased gravity as acceleration (m.s^{-2})	Total chrome oxide in feed reporting to concentrate %
392.4	50.4
588.6	67.5
882.9	87.6

Conclusion

The simulation proves that existing fluidisation models can be used to show the improvement in separation under artificially increased gravity. However, the lack of direct experimentation proving the effec-

tiveness of fluidisation models under these circumstances is notable and can form part of a new study.

The test work categorically shows that an increase in gravity ultimately causes an improvement in classification efficiency for the process challenge presented in this paper. A process that consists of applying conventional-pulse fluidised bed separators (jigs) followed by a screening-off of the larger particles, almost all of which will be slag particles, and finally recovery of the sub-200-micron ferro-alloy in a centrifugal separator is suggested. Unlike gold particles, the low returns that are offered by ferro-alloys on the open market will mean that optimisation of such a process would be required. In addition, the task will be made more complicated by the reality that the mass pulls of the concentrate are much higher than in gold recovery service.

Nomenclature

dp	particle diameter	(m)
dp_{1L}	particle diameter of the largest particle of the less dense species	(m)
dp_{2L}	particle diameter of the largest particle of the more dense species	(m)
dp_{1S}	particle diameter of the smallest particle of the less dense species	(m)
dp_{2S}	particle diameter of the smallest particle of the more dense species	(m)
e	voidage	
e_{fws}	free wet-settled voidage	
E_t	total bed expansion factor	
$F(dp)$	is the terminal velocity function for the particle size range	
g	is gravitational constant	(9.81 m.s ⁻²)
G	increased particle acceleration due to centrifugal forces	(m.s ⁻²)
$G(dp)$	is the function correlating particle size to bed mass fraction	
i	particle size increment of one micron for the denser species	(m)
j	particle size increment of one micron for the less dense species	(m)
l	refers to the largest particle present	(m)
M_T	is the total mass in the mixed zone for a particular gravity	
M_{Ti}	is the mass fraction of the less dense	

	species in a mixed zone	
M_{Tj}	is the mass fraction of the more dense species in a mixed zone	
n	empirical parameter of the Richardson and Zaki equation	
s	refers to the smallest particle present	(m)
U	empty tube linear fluid velocity ($e=1$)	(m.s ⁻¹)
U_t	is the terminal velocity of the particle derived from $F(dp)$	(m.s ⁻¹)
ρ_f	is the relative density of the discrete fluid	
ρ_c	is the relative density of the discrete finite element	
ρ_s	is the relative density of the solid particle	

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Author's short biography

Allan Nesbitt

Allan Nesbitt is presently a lecturer at the Cape Technikon. He has formally held positions at the University of Stellenbosch, Mintek (South African National Institute of Metallurgy), Caltex South Africa and South African Breweries. He received a Masters Degree in Chemical Engineering from the Cape Technikon in 1996. Allan's research interests lie in the fields of mineral processing, the application of artificial-intelligence systems and the mathematical modelling of particulate fluidisation and ion-exchange systems. The latter has already earned him a South African patent. He has published in accredited journals and presented scientific papers, both internationally and locally. In 2001, he received the Cape Technikon award for Most Promising Researcher of the Year, and recently started with a project towards his Doctorate.

Francis Petersen

Francis Petersen is a former head of the Department of Chemical Engineering at the Cape Technikon from 1998 to 2001. Currently, he is a visiting-Professor in the Department. He holds a BEng (Chem), MEng (Chem) and a PhD (Eng) from the University of Stellenbosch. He has published widely in accredited journals. Other academic achievements include being recipient of the Ernest Oppenheimer Memorial Trust Award for research excellence, a study-visit to Singapore on technology transfer and Researcher of the Year at the Cape Technikon. He serves on the South African Government Commission, addressing the problem of toxic waste disposal. Although he presently holds the position of General Manager (Research and Development) at Mintek (South African National Institute of Metallurgy), he is still actively involved in the Chemical Engineering Department in research relating to hydrometallurgy, biotechnology, water treatment and mathematical modelling.

Stephen Wanliss

Stephen Wanliss is currently completing his Masters Degree in the department of Chemical Engineering at the Cape Technikon. He graduated with a bachelor's Degree in Chemical Engineering Technology in 1997. His thesis is on the mathematical modelling of the characteristics of particulate fluidised non-spherical particles in a liquid medium.