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Intensification of flotation with an air-sparged hydrocyclone

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SYNOPSIS

Tests indicated that effective recovery of pyrite from a coarse Witwatersrand quartzitic ore can be accomplished by intensified flotation in an air-sparged hydrocyclone. Air is fed through the porous cylindrical wall of the hydrocyclone into a swirling layer of slurry. Hydrophobic particles are attached selectively to small air bubbles, which form a froth and are recovered through the overflow. Hydrophilic particles pass out in the underflow. A spigot in which flow is restricted by an orifice was found to be more successful in preventing blockage by wood chips than an annular opening between a pedestal and the cylinder wall.

Pyrite recoveries of 85 to 93 per cent at grades of 35 to 40 per cent sulphur were obtained in the air-sparged hydroclone with residence times of about 1 second. Comparative tests in a batch flotation cell after 320 seconds yielded average recoveries of up to 96 per cent, but with a mean grade of 32,5 per cent sulphur. A high collector dosage of 120 g/t was required in the cyclone, compared with the 40 g/t used in conventional operations. An air flowrate of about 150 l/min was adequate at a slurry feed rate of 35 l/min. Particle sizes between 38 and 106 μm yielded the best flotation results.

SAMEVATTING

Toetse het getoon dat doeltreffende herwinning van piriet uit 'n growwe kwartsitiese Witwatersranderts bewerkstellig kan word deur verskerpte flottasie in 'n luggeblaasde hidrosikloon. Lug word deur die poreuse silinderwand van die hidrosikloon in 'n malende laag flodder ingevoer. Hidrofobiese partikels word selektief aan klein lugborrels geheg wat 'n skuim vorm en deur die oorloop herwin word. Hidrofiliese partikels gaan in die onderloop uit. Daar is gevind dat 'n aftapkeel waarin vloeiing deur 'n opening beperk word, meer geslaagd as 'n ringvormige opening tussen 'n voetstuk en die silinderwand is om verstopping deur houtspaanders te voorkom.

Pirietherwinnings van 85 tot 93 persent met grade van 35 tot 40 persent swael is in die luggeblaasde hidrosikloon verkry met 'n verblyftyd van ongeveer 1 sekonde. Vergelykende toetse in 'n flottasiesel het na 320 sekondes gemiddelde herwinnings van tot 96 persent gelewer, maar met 'n gemiddelde graad van 32,5 persent swael. 'n Hoë versamelaardosis van 120 g/t was in die sikloon nodig vergeleke met die 40 g/t wat in konvensionele bewerkings gebruik word. 'n Lugvloeitempo van ongeveer 150 l/min was voldoende met 'n floddertoevoertempo van 35 l/min. Partikelgroottes tussen 38 en 106 μm het die beste flottasieresultate gelewer.

Introduction

The beneficiation of minerals by froth flotation is based upon controlled hydrophobicity. However, fine particles are recovered inefficiently, and this results in a loss to the tailings of large quantities of valuable minerals worldwide[1]. It has been found that every mineral has a limiting particle size below which its floatability decreases significantly, and that the probability of collision and attachment in conventional flotation cells is low owing to the relatively low intensity of the turbulence.

Consideration of these constraints led to the development of an air-sparged hydrocyclone (ASH) in the late 1970s at the University of Utah[2]. This device was designed to utilize the powerful centrifugal force developed in a cyclone, together with a high concentration of small bubbles, to achieve effective flotation of fine particles at an increased rate. Air is fed to the cyclone through its porous walls. Pressure relief of air-saturated slurries in a hydrocyclone has been proposed for enhancing the rate of flotation[3,4].

The rate of flotation in an ASH is limited by bubble-attachment phenomena, rather than by the rates of collision or air flow[5]. In this highly intensified flotation device, separations can be achieved for residence times of about 1 second, rather than minutes as in conventional cells. Miller and his co-workers demonstrated their concept successfully in the flotation in the ASH of oil shale[6], fine coal[7], copper sulphide ore[6,8], fine gold[9], resin from coal[10], and oil from water[11]. Fundamental work has also been performed on the swirl flow[5] and swirl-layer thickness[12], bubble formation[5,12], velocity profiles[12], Prandtl's mixing length[12], phase split[12], hold-up volume[13], and mean residence times[13].

The ASH has not been tested in the South African mining industry, although tens of millions of tons of gold-bearing pyritic ore pass annually through its flotation plants. The work by Burger[14] reported here was undertaken to study the applicability of Miller's ASH to the flotation of pyrite from a coarse Witwatersrand quartzitic gold ore. This paper reports the effects of operating variables on the efficiency of flotation in the ASH.

Experimental

Air-sparged Hydrocyclone and Ancillary Equipment

Fig. 1 shows a schematic diagram of the ASH used by

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Burger[14], its basic features being similar to those of the ASH tested by Miller and his co-workers[5-10]. The porous cylinder has pores with a median size of 1,0 μm and is arranged vertically, with tangential slurry feed at the top, froth overflow through the central vortex finder, and an annular opening between the wall and the pedestal for the downward flow of tailings. Air bubbles sparged radially through the ceramic porous wall are dispersed by the high velocity of slurry in swirl flow countercurrent to the rising froth phase. Miller and Van Camp[7] recommended that a vertical cyclone with tangential feed at the top would be the preferred design.

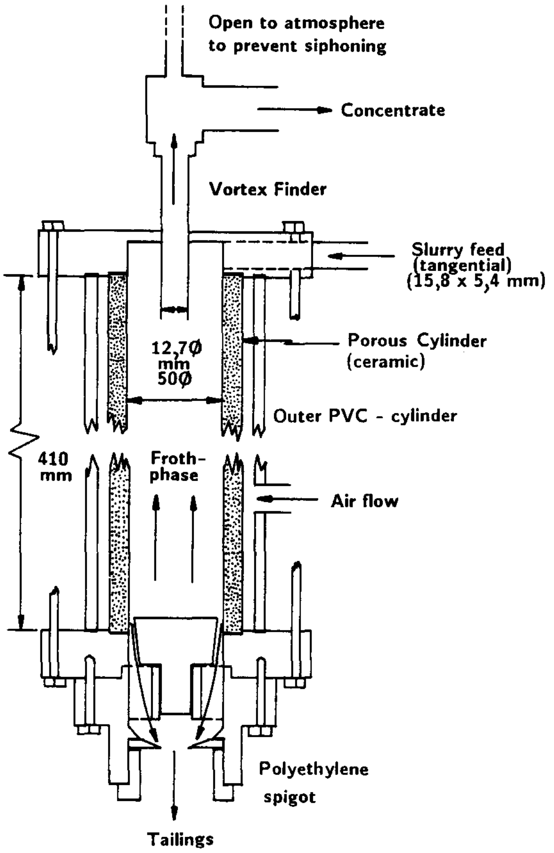

Fig. 1—Schematic diagram of the air-sparged hydrocyclone

Miller *et al.*[15] used both an annular discharge and a valve downstream as underflow-discharge devices, and surmised that a pedestal would be required to support the inner froth core[5,14]. A conical brass pedestal mounted on a screw thread to vary the annular outlet opening was used in some of the work reported here. It was found that small quantities of wood chips or larger particles caused blockages in the narrow annular gap.

Consequently, a new spigot made of high-density polyethylene was designed by Burger[14] to eliminate blockages. The main feature of this design, shown in Fig. 1, was that the limiting area of the orifice opening below the pedestal was smaller than the annular area between the pedestal and the cylinder. This pedestal had a diameter of 46,5 mm. An orifice diameter of 15,0 mm was used when the effect of diameter was not being investigated. Burger[14] found that the results were not influenced significantly by the length of the vortex finder, so that this variable was kept constant at 50 mm.

The ASH was incorporated in a simple rig, in which feed slurry was taken from a recycle stream round an agitated conditioning tank with a volume of 470 litres. A magnetic flowmeter was used to monitor the feed slurry pumped by a centrifugal slurry pump.

Characteristics of the Ore

The ore used was an easily floatable coarse pyritic ore from the reclaimed dumps of Ergo Ltd on the eastern Witwatersrand. The average sulphur content was 1,74 per cent by mass (which corresponds to 3,26 per cent FeS_2), and the absolute density was 2747 kg/m^3. Table I gives the particle-size distribution, as well as the distribution of sulphur with size fraction. It is clear that 68 per cent of the sulphur in the ore was present in the fraction between 53 and 150 μm. All the particles passed through a 300 μm sieve.

TABLE I

DISTRIBUTION OF PARTICLE SIZE AND GRADE OF SULPHIDE IN THE ORE

Size fraction μm	Mass %	% in size range	Mass % of total S in ore in size range
+ 212	11,5	0,322	2,13
+ 150	30,0	0,748	13,0
+ 106	22,4	2,08	26,9
+ 75	15,5	2,70	24,2
+ 53	9,3	3,14	16,8
+ 38	2,8	3,61	5,82
− 38	8,5	2,29	11,2
All fractions	100,0	1,74	

Operating Procedures

The slurry was prepared from tap water and fresh ore taken from sealed drums. Commercial-grade potassium amyl xanthate (a collector) and a proprietary frother (Dowfroth 250: polypropylene glycol methyl ether) were added to the slurry at a pH value of 4,0 to 4,5 before conditioning for 10 minutes. Most of the runs used feed slurries of 10 per cent solids by mass containing 160 g/t of collector and 30 to 50 p.p.m. of frother, although some tests were done under different conditions.

Samples of overflow and underflow products from the ASH were taken simultaneously and weighed. Discrepancies in the mass balances for sulphur, total solids, and water were below 5 per cent. The solids were filtered, dried, and assayed for sulphur, and the particle-size fractions were determined by dry sieving down to 38 μm and wet sieving below that size.

Batch Flotation Tests

A set of experiments was also performed on the same ore and reagents in a 3-litre modified Leeds batch laboratory flotation cell. The conditions used were 30 per cent solids by mass, an air flowrate of 6,5 l/min, a pH value of 4,5, a froth height of 2,4 cm, a frother addition of 50 p.p.m., a collector addition of 40 g/t, a water feed rate for froth drainage of 0,03 l/min, and a stirring speed of 1500 r/min.

Results and Discussion

Recovery of Water with No Solids Present

In some experiments, clear water containing no reagents was fed to the ASH in order to characterize its flow behaviour by use of the simplest possible system. Figs. 2 and 3 depict the results for the two types of spigots used.

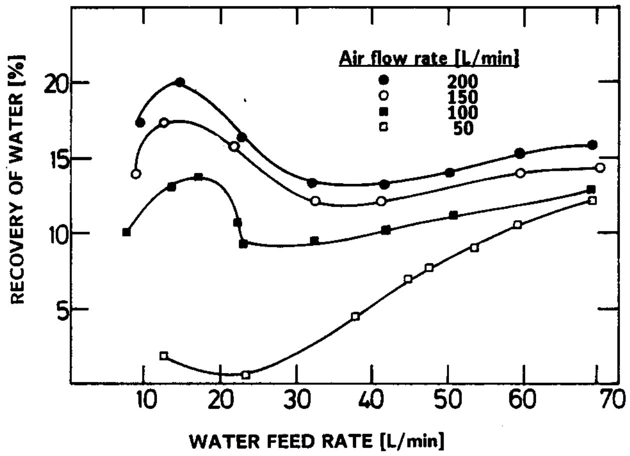

Fig. 2—Recovery of water in the overflow with no solids present, using the brass pedestal of 48,0 mm diameter

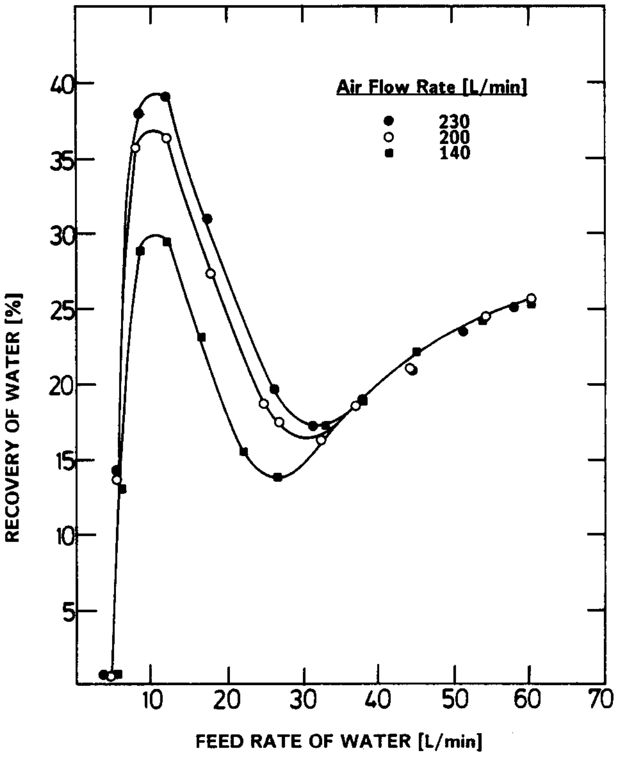

Fig. 3—Recovery of water in the overflow with no solids present, using the polyethylene spigot with an orifice diameter of 15,0 mm

Miller *et al.*[5,12] observed that the thickness of the swirl layer in an unrestricted vertical cylinder increased slightly with axial distance from the header. Baker *et al.*[13] observed that the thickness of the swirl layer in a restricted cylinder was 5 to 7 per cent of the diameter of the cylinder, and increased with both air flowrate and water flowrate.

It can be expected that the flow of air reduces the effective centrifugal force experienced by a fluid element. For water feed rates of less than about 15 l/min, the centrifugal forces were so weak that water was easily entrained. Figs. 2 and 3 show that an increase in the water feed rate within this range resulted in an increased recovery of water in the overflow. As the feed rate of water increased further, its centrifugal force overcame the entraining effect of air to reduce the recovery to a minimum.

At higher feed rates of water, and therefore greater thickness of the swirl layer, the restricting effect of the annular opening or orifice area forced more water to the overflow. With an increase in the air flowrate, an increased feed rate of water was required to counteract the entraining effect of the air, so that the position of minimum recovery moved to the right in Figs. 2 and 3. The minimum recovery occurred at a feed rate of 40 l/min when frother was added.

Figs. 2 and 3, as well as further work by Burger[14], showed that both the negative and the positive slopes of the recovery curves for the orifice-limiting spigot were steeper than those for the conical brass pedestal. It is noteworthy that the flowrate of air did not appear to have any effect on the recovery of water in the range of higher water feed rates when an orifice-limiting spigot was used.

Recovery of Water and Solids Using Reagents

Figs. 4 to 9 illustrate the recovery of water, total solids, and sulphur under different operating conditions. The general trends of these curves is discussed below.

According to Figs. 4 to 6, the water recovery was similar to that observed in Figs. 2 and 3. It appears as though the recovery of water was higher when solids were present, probably owing to the increased thickness of the swirl layer[12] and the stabilization of the froth phase by fine particles[15]. In general, the recovery of solids decreased sharply as the feed rate of slurry to the ASH increased.

Burger[14] showed that, when no reagents were used, only particles smaller than 38 μm were entrained significantly to the overflow at slurry feed rates higher than about 35 l/min. The recovery of sulphide particles larger than 38 μm was inhibited at higher feed rates of slurry, while the opposite held[5,8,14,15] for particles smaller than 38 μm. High turbulence and strong centrifugal forces tend to rupture the hydrophobic particle–bubble aggregates, yet increase the collision efficiency of small particles[16,17].

According to Figs. 7 to 9, the grade of sulphur in the concentrate showed a general increase with an increase in centrifugal force at lower feed rates of slurry. A maximum grade was attained near the slurry feed rate that yielded the minimum recovery of water. It is noteworthy that the decreased recovery of total solids at lower feed rates of slurry was associated with an almost constant recovery of sulphur. This means that the increased centrifugal force had a cleaning action on the froth[5,15] so that the increase in grade is understandable.

An unexpected change in the shape of the grade curves (Figs. 7 to 9) and in the recovery of total solids (Figs. 4 and 6) occurred at a slurry feed rate between 30 and 40 l/min. This behaviour was more pronounced for the coarse particles, and was reproducible[14].

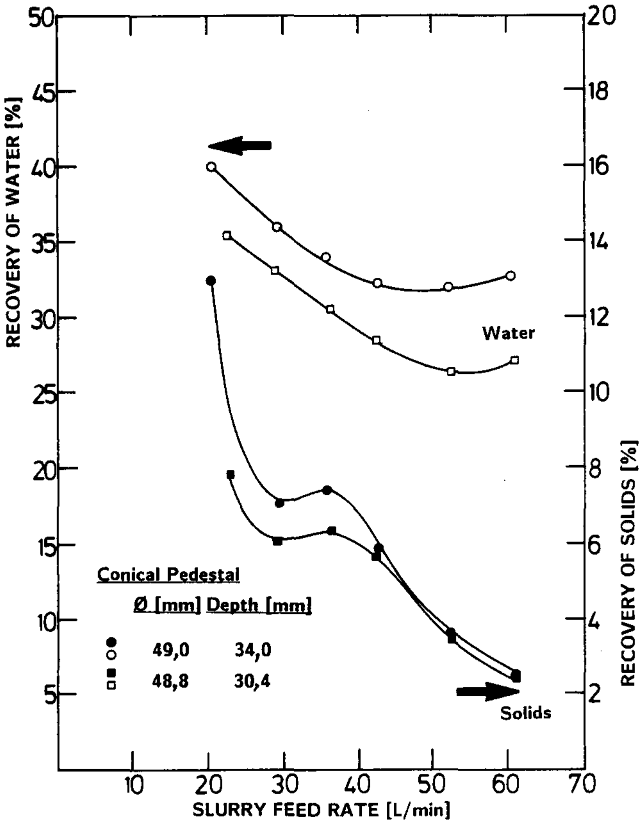

Fig. 4—Recovery of water and solids at two diameters of the brass pedestal (solids in feed = 30 mass %, air flowrate = 205 l/min, collector = 80 g/t, frother = 50 p.p.m.)

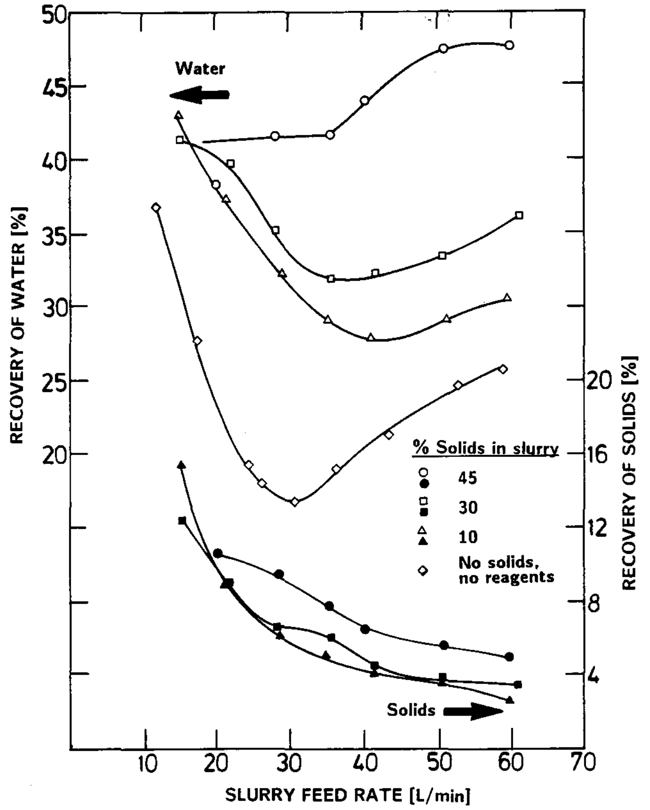

Fig. 6—Recovery of water and solids at different densities of slurry using a polyethylene spigot (air flowrate = 200 l/min, collector = 160 g/t, frother = 35 p.p.m.)

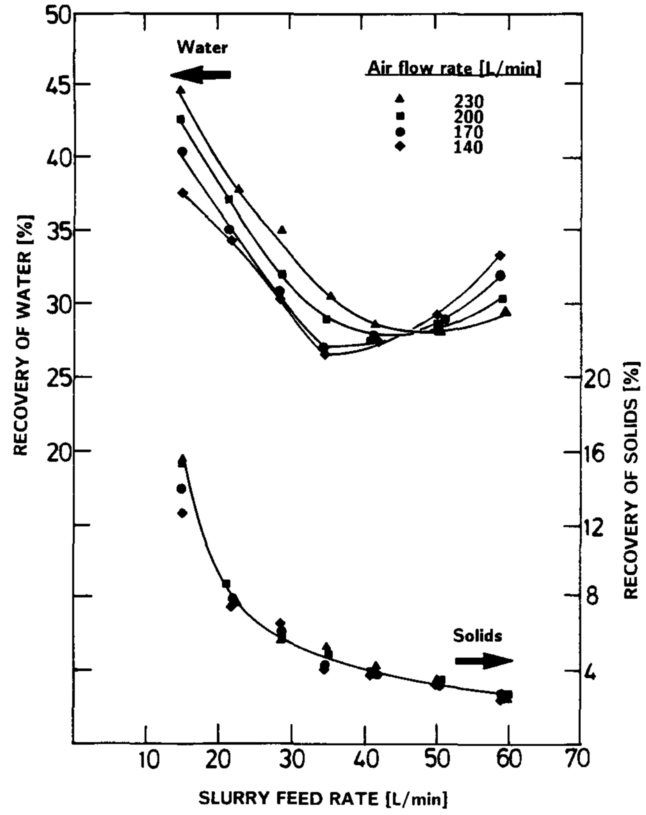

Fig. 5—Recovery of water and solids at different flowrates of air using a polyethylene spigot (solids in feed = 10 mass %, collector = 160 g/t, frother = 35 p.p.m.)

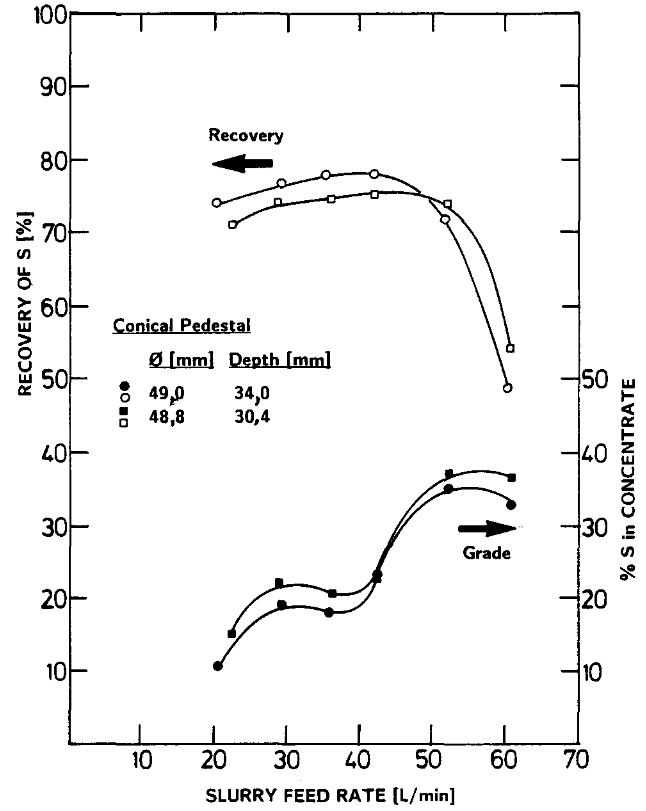

Fig. 7—Grade and recovery of sulphur at two diameters of the brass pedestal (solids in feed = 30 mass %, air flowrate = 205 l/min, collector = 80 g/t, frother = 50 p.p.m.)

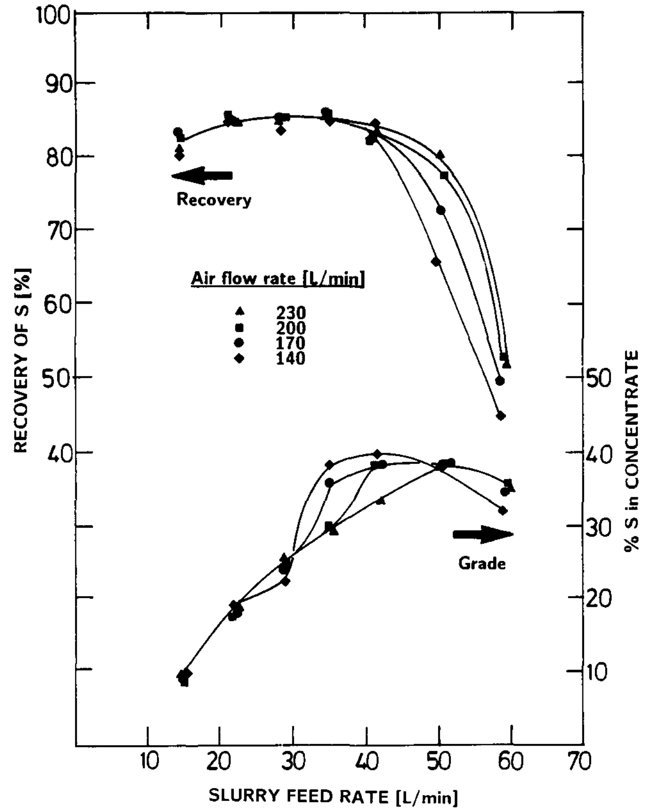

Fig. 8—Grade and recovery of sulphur at different flowrates of air using a polyethylene spigot (solids in feed = 10 mass %, collector = 160 g/t, frother = 35 p.p.m.)

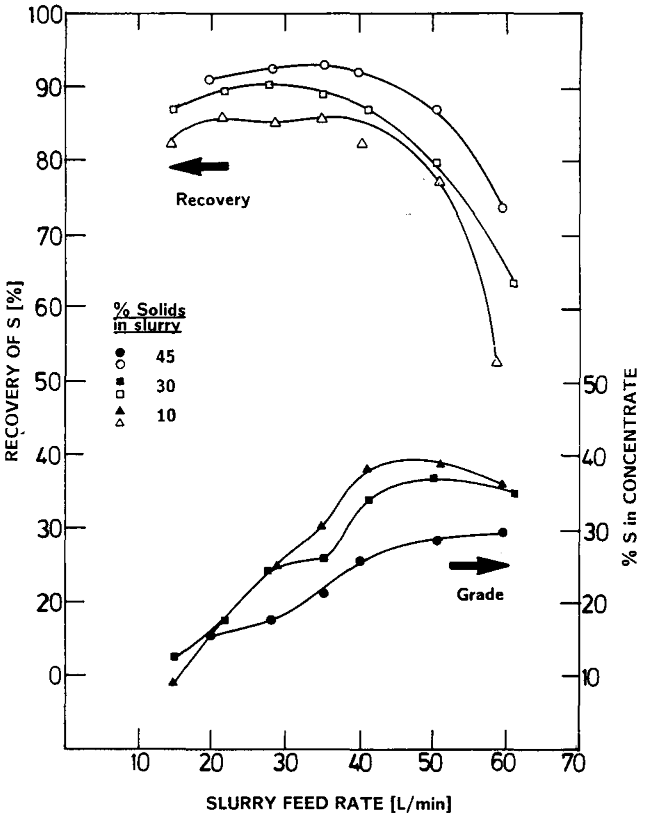

Fig. 9—Grade and recovery of sulphur at different densities of slurry using a polyethylene spigot (air flowrate = 200 l/min, collector = 160 g/t, frother = 35 p.p.m.)

These tests showed that the ASH as used by Burger is capable of a pyrite recovery of over 85 per cent and a concentrate grade of 40 per cent sulphur (i.e. 75 per cent FeS_2) at slurry feed rates of between 30 and 40 l/min. Such results compare favourably with those normally obtained for rougher flotation in plants operating on the same ore.

Effect of Underflow Opening

Figs. 4 and 7 show results for conical brass pedestals of diameters 48,8 and 49,0 mm, which extended 30,4 and 34,0 mm respectively into the porous cylinder. A reduction of 16,5 per cent in the annular area (Fig. 4) increased the recovery of water at all slurry feed rates, and caused a smaller increase in the recovery of total solids. The recovery and grade of sulphur were not affected significantly.

Effect of Air Flowrate

Fig. 5 illustrates an increase in water recovery with an increase in air flowrate at lower slurry feed rates, and a concomitant shift of minimum water recovery to higher slurry feed rates. This behaviour can be explained in the same way as that observed for Figs. 2 and 3. It is evident that the recovery of total solids was not influenced by the flowrate of air, and it is therefore surprising that the flowrate of air affected the recovery of water adversely at high slurry feed rates.

An increase in the air flowrate (Fig. 8) enhanced the recovery of pyrite, especially at high slurry feed rates. This effect was similar for all the size fractions, which could indicate that the dense pyrite particles were recovered preferentially in the froth.

Effect of Slurry Density

The significant increase in water recovery obtained with increased solids content of the slurry is illustrated in Fig. 6. The throttling effect of the spigot with an increase in the solids content from 30 to 45 per cent was the likely cause of the dramatic increase in the recovery of water, especially at high slurry feed rates.

An enhanced recovery of total solids and pyrite, together with a decrease in the sulphur grade with increased solids content of the feed, was measured as shown in Figs. 6 and 9. The shapes of the curves for the recovery of water do not appear to be influenced significantly by the solids content, apart from the curve for 45 per cent solids. This means that a relatively dilute slurry could be used in studies on an ASH.

Effect of Collector Addition

The particle–bubble aggregates could become more stable with increased additions of collector[18]. This, in turn, would stabilize the froth and increase the recovery of water, as is evident from Fig. 10. It is significant that the addition of collector exerted an influence only at higher slurry feed rates, where high centrifugal forces come into effect.

When the addition of collector was increased, the point of minimum water recovery tended to occur at lower slurry feed rates. An increase in the recovery of pyrite at all feed rates of slurry is shown in Fig. 11. It is difficult to draw a general conclusion about the effect of

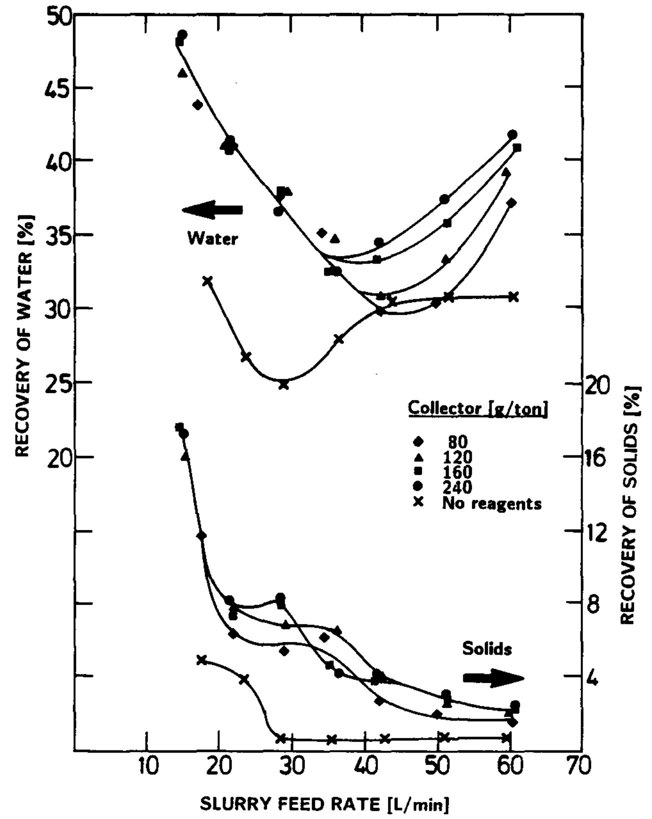

Fig. 10—Recovery of water and solids at different additions of collector (diameter of brass pedestal = 49,0 mm, solids in feed = 10 mass %, air flowrate = 205 l/min, frother = 30 p.p.m.)

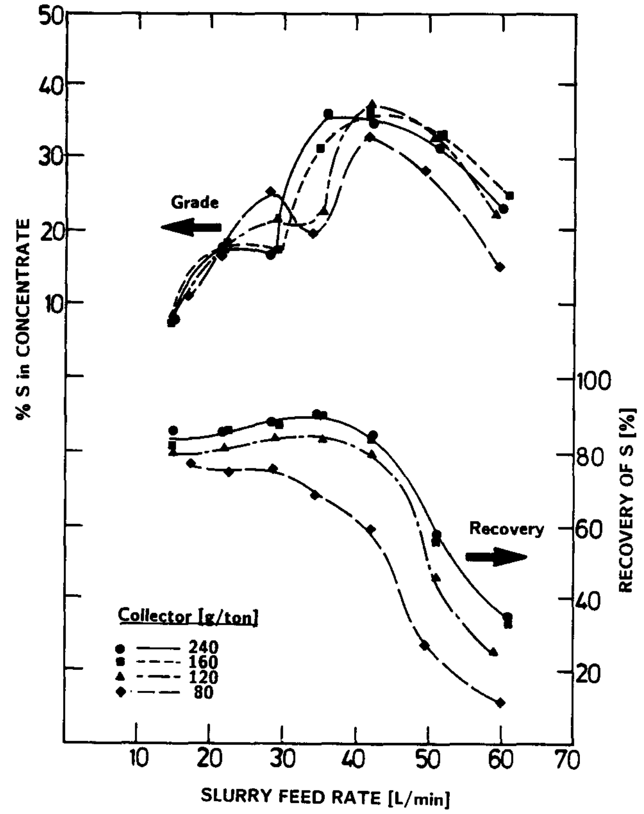

Fig. 11—Grade and recovery of sulphur at different additions of collector (diameter of brass pedestal = 49,0 mm, solids in feed = 10 mass %, air flowrate = 205 l/min, frother = 30 p.p.m.)

collector addition on the recovery of total solids or the grade of concentrate.

An addition of 120 g/t seems to be sufficient for this type of ore. The dosage of 40 g/t that is used in conventional plants would have been quite inadequate, owing to the high shearing forces on the particle-bubble aggregates in the ASH.

The influence of collector addition revealed the same trends for all size fractions, but the sulphur grade of the coarser particles appeared to be enhanced relatively more.

Effect of Frother Addition

Miller *et al.*[12] showed that the recovery of water increased with increased addition of frother. This effect is confirmed by the results illustrated in Fig. 12, which show that the increased recovery of water at all feed rates of slurry was accompanied by an increase in the recovery of solids.

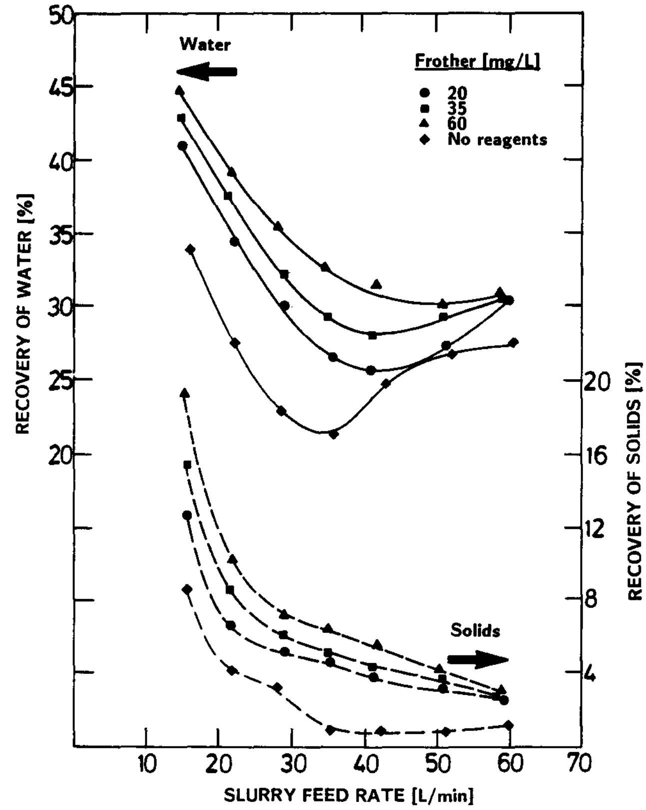

Fig. 12—Recovery of water and solids at different additions of frother using a polyethylene spigot (solids in feed = 10 mass %, air flowrate = 200 l/min, collector = 160 g/t)

The corresponding decrease in sulphur grades shown in Fig. 13 was a result of this enhanced recovery of hydrophilic particles. At slurry feed rates below 40 l/min, the recovery of pyrite decreased with an increase in frother addition. This behaviour was the opposite to that observed for conventional flotation.

Fig. 14 shows the recovery and grade curves for all the particle-size fractions at a slurry feed rate of 35 l/min. The shapes of these curves are explained by Burger[14], and are similar to those observed by Miller *et al.*[5,15]. At slurry feed rates higher than 40 l/min, a more stable froth resulting from increased additions of frother enhanced

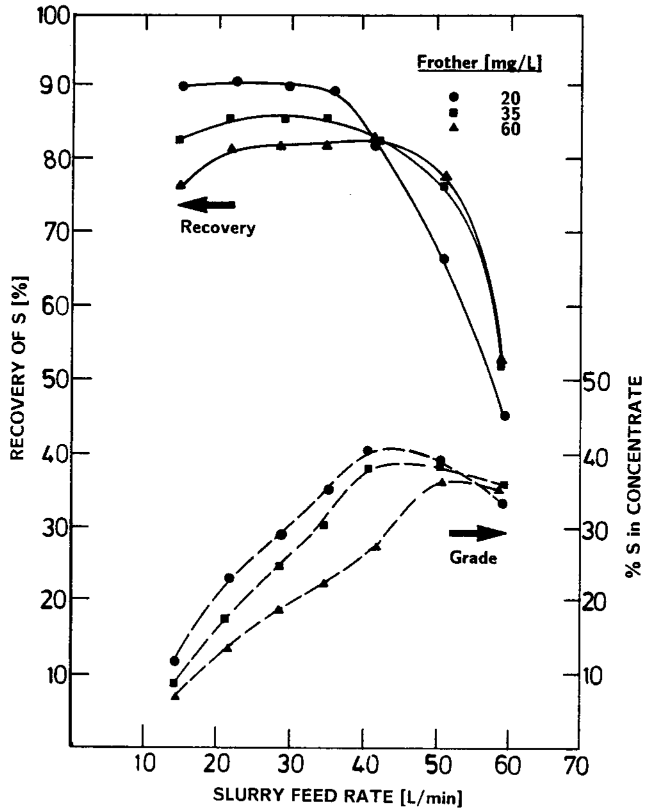

Fig. 13—Grade and recovery of sulphur at different additions of frother using a polyethylene spigot (solids in feed = 10 mass %, air flowrate = 200 l/min, collector = 160 g/t)

the recovery of pyrite, as illustrated in Fig. 13. Baker *et al.*[13] showed that frother additions above 40 p.p.m. did not have any significant influence on the hold-up volume in the ASH.

Comparison with Batch Flotation

The batch results shown in Fig. 15 demonstrate that all the size fractions yielded recoveries of over 90 per cent after 300 seconds. Burger[14] obtained recoveries of pyrite of up to 96 per cent after 320 seconds, but with a relatively low average sulphur grade of 32,5 per cent.

These batch results could be used in a comparison of the performance of the ASH with that of a conventional rougher cell[13]. The mean residence time for a similar ASH was measured as 0,5 to 1,0 second[13]. The throughput per unit volume of the ASH is thus about 300 times that of a conventional cell.

Burger[14] observed an optimal addition of collector of 50 g/t during batch flotation. For short residence times, an increased addition of collector significantly decreased the recovery of pyrite. This phenomenon is known as over-xanthating[19]. In comparison with the results illustrated in Fig. 11, it is clear that significantly lower additions of collector were required in the batch cell.

Conclusions

Pyrite can be recovered effectively from a coarse Witwatersrand quartzitic ore by intensified flotation with an air-sparged hydrocyclone (ASH). Recoveries of pyrite from 85 to 93 per cent at grades of 35 to 40 per cent sulphur were obtained in the ASH. Optimal recoveries and grades were obtained for particles between 38 and 106 μm.

The separation achieved after 0,5 to 1 second in the ASH was comparable with that attained in conventional batch flotation tests after 300 seconds. The ASH has a potential advantage over conventional cells in its very high throughput per unit volume, which was 300 to 1 for this ore.

A disadvantage of the ASH is that it requires three times as much collector as a conventional flotation cell.

The proposed new design of an orifice-limiting spigot instead of an annular-limiting spigot proved to be successful in preventing blockage by wood chips.

Acknowledgements

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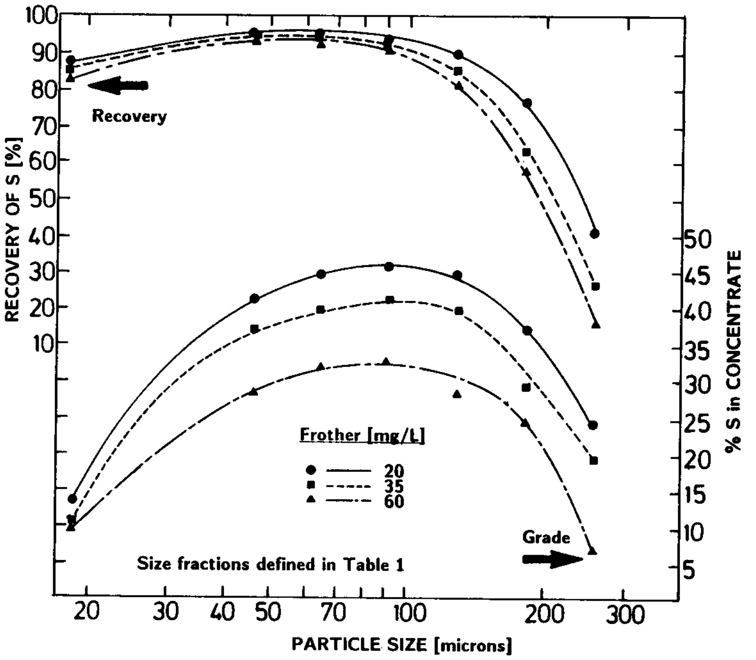

Fig. 14—Effect of different additions of frother on the grade and recovery of sulphur in different size fractions, using a polyethylene spigot (solids in feed = 10 mass %, air flowrate = 200 l/min, collector = 160 g/t, slurry feed rate = 35 l/min, for 'microns' read 'μm' or 'micrometres')

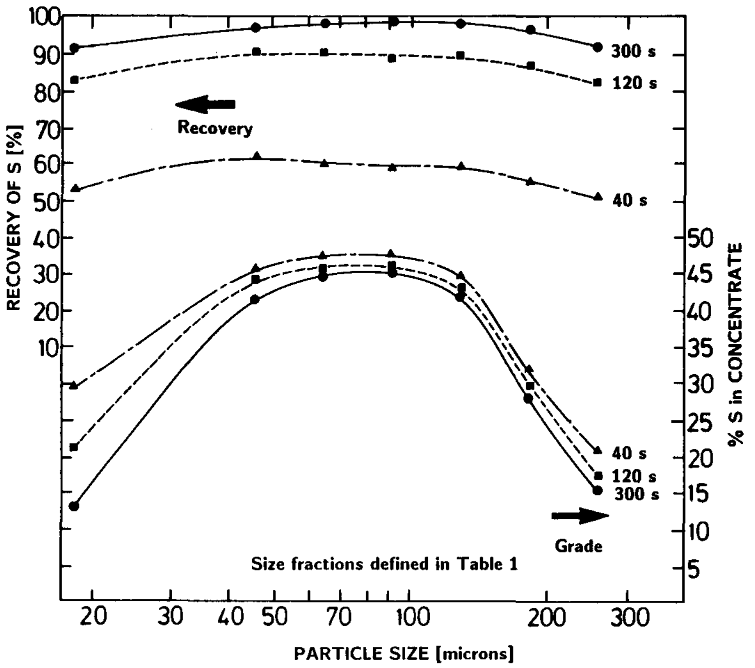

Fig. 15—Grade and recovery of sulphur for different size fractions in batch flotation (for 'microns' read 'µm' or 'micrometres')

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