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REMOVAL OF FINE GANGUE MINERALS FROM CHADOR-MALU IRON CONCENTRATE USING HYDROSEPARATOR

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Abstract: Phosphorus and silica are the main impurities of the Chador-malu iron ore which need to be reduced to the required values of 0.1 and 2%, respectively. The impurities in the final iron concentrate are mainly due to the presence of fine particles (less than 25 μm) of silica and apatite in the concentrates of magnetic separators and flotation circuits. In this study, the removal of very fine gangue minerals from iron concentrate of the Chador-malu processing plant was investigated using a laboratory hydroseparator. The laboratory-scale hydroseparator experiments were conducted under various operational conditions. The results showed that the silica and phosphorus contents of the flotation feed samples (less than 45 μm) decreased from 4.13% and 0.58% to 2.90 and 0.45%, respectively, while the iron grade increased from 59.5% to 63.5% by setting the effective parameters of the separator. The follow up flotation tests on the hydroseparator product resulted in an iron concentrate with silica and phosphorus contents of less than 2% and 0.04%, respectively. Moreover, its phosphorus content was reduced from 0.66% to 0.1% by desliming the final magnetic concentrate with hydroseparator. In this case, around 76% of phosphorus was removed.

Keywords: *Chador-malu plant, iron concentrate, silica, phosphorus, hydroseparator*

Introduction

Steel industries require a high grade iron concentrate with specified levels of impurities such as phosphorus and silica. Iron ores normally undergo two or more stages of grinding which results in producing fine particles. The fine particles have deteriorating effects on the subsequent separation processes such as magnetic separation and flotation (Wills, 2011; Mc Nab et al., 2009).

Processing of iron ores using gravity methods has been practiced for many years although these methods have been replaced by flotation and magnetic methods (Burt,

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1999). Shaking table, spiral, and hydrocyclone are common equipment used for processing of fine iron ore in the laboratory or industrial scales. Using the above mentioned methods to process fine iron ores has not resulted in satisfactory separation efficiencies (Subrata, 2009; Surkov and et al., 2008). Besides, magnetic and flotation methods have also been used for separation of fine iron ore particles. The presence of fine particles in flotation process causes an extensive use of collectors and increases the viscosity of pulp (Rocha et al., 2010; Wills, 2011). Fine iron ore particles can also decrease the efficiency of magnetic separators (Arol and Aydogan, 2004). Many studies have been conducted to improve the separation efficiency of gravity separators. Subrata (2009) carried out some studies on the recovery of fine iron ore particles through multi-gravity separators. However, the cost and complexity of the operation has limited the use of such separators.

A significant number of studies in Australia and India have been carried out to classify the particles through some types of fluidized bed separators since the beginning of the twentieth century. These studies have indicated that these types of separators classify particles based on their size and mass, and are suitable for particles less than 75 µm. The fluidized bed separators can be also used in removing the impurities, including silica and alumina, from coal and heavy ores such as iron, manganese, and chromite.

Hydroseparator is a type of hydraulic classifier with a mechanism similar to fluidized bed separators. This separator works with hindered settling mechanism using an upward stream of water. These devices have become increasingly popular because of high efficiency and capacity, and low capital and operational costs. Moreover, they have a relatively better separation efficiency compared to hydrocyclones (Tripathy et al., 2015; Sunil et al., 2013; Murthy and Basavaraj, 2012; Sarkar et al., 2008b; Luttrell, 2006; Sarkar et al., 2006; Drummond et al., 2002). Hydroseparator is widely used in iron ore processing plants in Australia with good metallurgical results. It has been used for removing fine particles from flotation feeds and final iron concentrates (David et al., 2011). Magnetic hydroseparators have reported to be used for extraction of hematite and magnetite from iron ores in Russia and the United States. Even though this device is more efficient than hydroseparator for removing silica particles, financial considerations may limit its use at industrial scale. Moreover, it is more difficult to control the operational parameters of this device (Stafeev, 2011).

In the present study, a laboratory hydroseparator was designed and constructed to investigate the separation of fine silica and phosphorus particles from the final concentrate of Chador-malu processing plant including low intensity magnetic concentrate and flotation feed.

Chador-malu processing plant

Chador-malu mine, the largest iron mine in Iran, produces around 11 Tg of iron concentrate per year. The iron ore contains magnetite and hematite minerals. The ore is processed in 5 parallel production lines. Each line processes around 400 Mg per hour of ore to produce iron and apatite concentrates. The final iron concentrate of Chador-malu processing plant is a mixture of magnetite and hematite concentrates. After primary crushing, iron ore is fed to the autogenous (AG) grinding mill. The product of AG mill, with d_{80} of around 200 μm, is sent to the medium intensity magnetic separators. The concentrate of these separators is ground in a ball mill in close circuit with hydrocyclones. The overflow of hydrocyclones, with d_{80} of about 42 μm, is sent to the cleaner magnetic separators. The tailings of cleaner stage are fed to the high-intensity magnetic separators. The concentrate of high-intensity separators enters a regrind ball mill, having a d_{80} of about 45 μm, enters the reverse flotation circuit for a final dephosphorization. The tailings of high-intensity magnetic separator are transferred to apatite flotation circuit to recover the apatite.

The silica and phosphorus contents of Chador-malu iron concentrate needs to meet the requirements of steel industry at the specified levels of less than 2% and 0.10%, respectively (Mark, 2012).

The separation mechanism in hydroseparator

Hydroseparators are basically working with hindered settling mechanism. The main feature of this device is the presence of a stream of water opposing the particle's direction of settling. The separation mechanism of the particles in hydroseparator can be explained by the well-known Richardson & Zaki (1954) equation:

$$V_{slip,ij} = U_{ter,ij}\varepsilon^{n_{ij}-1} \tag{1}$$

In Eq. 1, $V_{slip,ij}$is the velocity of the falling particle, $U_{ter,ij}$is the settling speed of the particle in an unstable bed, ε is a function of viscosity, n_{ij} is Richardson & Zaki's constant factor which is a function of Reynolds number, and i and j represent the size and density, respectively.

When the particles enter the hydroseparator from the top, with water stream flowing from the bottom (fluidization water), a bed is created which can act as a perfect mixture. A fluidized bed, also known as hindered settling region, is created by entering the feed downward from the top of the vessel and water flowing upward from the bottom of the vessel. At this point, the particles of the bed are in an unstable condition (Tripathy et al., 2015; Luttrell et al., 2006). Each of the particles in the bed is free to move around, they go over a spin cycle. The ideal situation for separation is when the particles in the bed have the required time to spin and collide with each other. Therefore, it is necessary not only to give this time to the particles, but also to increase the density of the particle in the fluidized bed for the separation condition to be provided. The behavior of this mixture is like a fluid with high viscosity and particle with higher density can slowly sink into the fluidized bed and make their way to the concentrate. The lighter particles go up with the stream of water to the overflow (Tripathy et al., 2015; Luttrell et al., 2006; Sarkar et al., 2008). Therefore, any factor that affects the formation of the fluidized bed, will affect the efficiency of separation in the hydroseparator.

Materials and methods

Sample characterization

As already mentioned, the main purpose of this research was to investigate the possibility of removing fine impurities from an iron concentrate. The fine particles decrease the efficiency of magnetic and flotation separators. Two types of samples were prepared: one from the feed to the dephosphorization flotation circuit (Case-1), and another from the feed to the cleaner magnetic separators (Case-2). The chemical composition and distribution of iron, silica and phosphorus in these samples were examined. The results are shown in Table 1, and Figs. 1 and 2.

Table 1 shows that both samples have a significant amount of iron, and the main impurities are phosphorus and silica. Figures 1 and 2 show that considerable amount (more than 50%) of silica and phosphorus entering the flotation system and the magnetic separators are contained in the size fractions smaller than 25 µm. The d_{80} of the feed of flotation and cleaner magnetic separator are 44 and 42 µm, respectively.

Table1. Chemical analysis of the feed to the flotation and cleaner magnetic circuits of Chador-Malu plant

Components	Fe%	SiO_2 %	Al_2O_3%	CaO%	MgO%	TiO_2 %	Mn%	P%	V%
Flotation Feed	59.41	4.13	0.848	3.166	0.824	0.242	0.032	0.576	0.159
Magnetic Feed	62.04	2.71	0.512	3.321	0.599	0.451	0.05	0.659	0.649

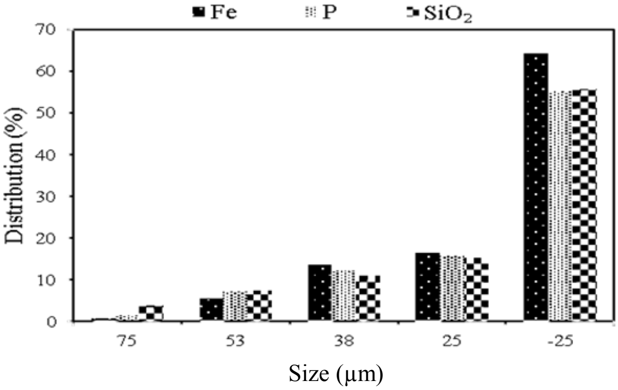

Fig. 1. Distribution of iron, phosphorus, and silica contents of flotation feed as a function of particle size

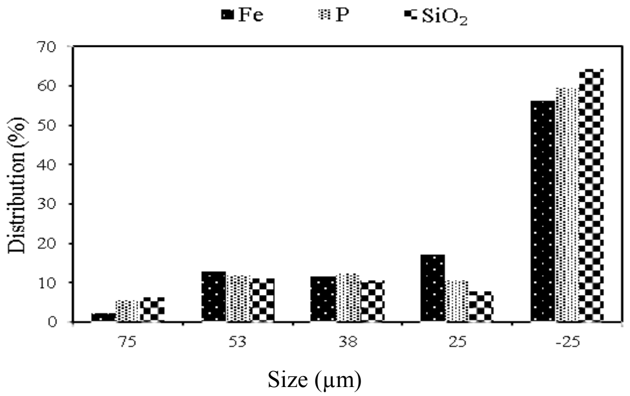

Fig. 2. Distribution of iron, phosphorus, and silica contents of magnetic separator as a function of particle size

The liberation analysis of particles was conducted through thin sections, and particle counting of the samples. It was shown that in the feed samples of flotation and magnetic separators a major part of silica and phosphorus particles were free in the size fraction less than 38 μm. Minerals containing phosphorus and silica were mostly apatite and quartz. The dominant mineral in the flotation feed were hematite while it was magnetite in the magnetic cleaner feed. Considering Figs. 1 and 2, and the presence of a high amount of phosphorus and silica in below 25 μm size fractions, more samples from the circuits were taken to investigate the performance of magnetic cleaner and flotation processes, in removing the fine particles from the feed materials. Figures 3 and 4 show the distribution of iron, phosphorus, and silica in the concentrates of cleaner magnetic and flotation circuits of Chador-malu plant, respectively.

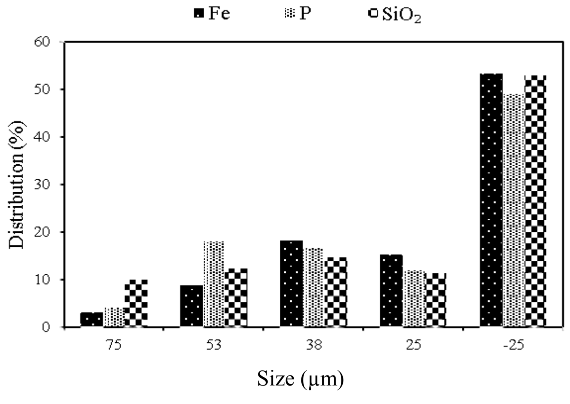

Fig. 3. Distribution of iron, phosphorus, and silica contents of Chador-malu final magnetic concentrate as a function of particle size

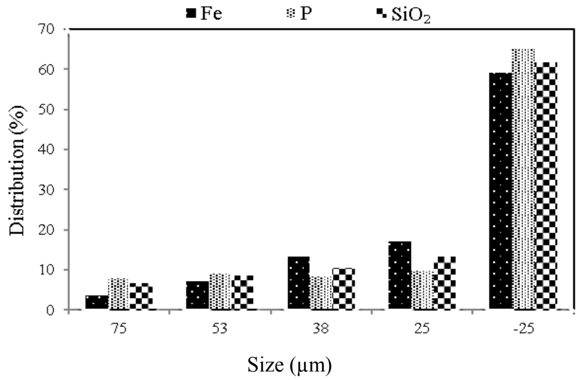

Fig. 4. Distribution of iron, phosphorus, and silica contents
of Chador-malu final flotation concentrate as a function of particle size

As indicated, more than 60% of phosphorus and silica in the flotation concentrate and around 40% to 50% of phosphorus and silica of the magnetic concentrate are in the size fractions of less than 25 μm. Therefore, the flotation and magnetic processes of Chador-malu plat are not capable of removing the phosphorus and silica particles in the range of fine particles. The presence of phosphorus, in the range of fine particles, in the magnetic concentrate, could be due to the hydraulic conveyance of gangues or their entrapment in the magnetic flocks. In the flotation process, fine particles have low collision efficiencies with gas bubbles and float slowly.

Experiments with hydroseparator

The experiments were conducted using a hydroseparator device that was designed and constructed for this study. The designed device consisted of a vertical tank with a square shaped cross section and the bottom part was a pyramid-shaped tank. The dimensions of the square shaped tank were 24×24×55 cm, and the pyramid was 25 cm long from the bottom to the top. An adjustable bypass valve was installed at the bottom of the pyramid. A feed well, adjustable in height from 0 to 30 cm, was designed to feed the hydroseparator. The pulp was entered the device from the top and center through the feed well. Water was directed upward through meshed pipes, located at the bottom of the main tank. Figure 5 indicates a general schematic diagram of the test rig. A peristaltic pump was used to adjust the water flow. Primary tests showed that a minimum of 11000 g/min was needed to have a stable loading and maintain a fluidized bed. During the experiments, in short time intervals, the samples from the hydroseparator overflow and underflow were taken. In the conducted experiments, the solid percentage was 35%. First, at constant upward flow of water and the feeding well height, by changing the underflow rates from 3.5 dm^3/min up to 20 dm^3/min, a suitable underflow and subsequent overflow regime were determined. Then, using the underflow discharge rate, from previous experiments, by changing the upward water flow rate from 12 to 45 dm^3/min, at two levels of feed well height of 10 and 17 cm, experiments were conducted and suitable water rate and feed well height were determined.

Some experiments were conducted using the flotation circuit feed (dephosphorization of hematite) to determine the effects of operation conditions on the performance of the hydroseparator device. The controllable operational parameters of the device including: the upward water flow, the height of the feed well and the underflow discharge rate, were tested. In addition, in similar conditions, some experiments were conducted on the feed samples of cleaner magnetic separators of Chador-malu processing plant, to investigate the possibility of reducing its phosphorus content. The results of these experiments, using hydroseparator, are presented in the following chapter.

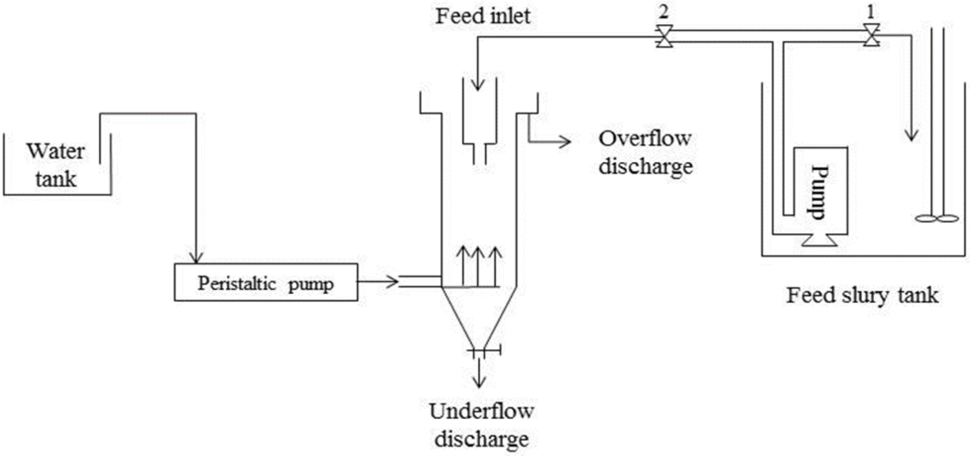

Fig. 5. A schematic diagram of hydroseparator test rig

Results and discussion

Effect of underflow discharge rate

To investigate the effects of underflow and overflow discharge rates, some experiments were conducted by using constant rate of upward water (25 dm^3/min) and at feed well height of 10 cm. Figure 6 indicates that as the underflow rate increased from 3.5 to 10.5 dm^3/min, the gangue content of the concentrate (underflow) increased. When the underflow discharge was at the minimum level (3.5 dm^3/min), the silica and phosphorus contents of the concentrate reduced to 2.80% and 0.38%, respectively. The results show that as the underflow rate increased from 10.5 to 12.5 dm^3/min, both quality of underflow product (Fe, 64.7%) and recovery (73.8%) increased. By increasing the underflow rate from 12.5 to 20 dm^3/min, the gangue content of the concentrate increased. In this case, the recovery slightly increased. It is likely that the fluidized bed inside the hydroseparator formed at equal rates of overflow and underflow. At this state more selective separation can happen (Sarkar et al., 2008). In other words, the discharge rate of 12.5 dm^3/min in combination with the settings of other parameters, provided a balance on the acting forces on the settling of the particles, and therefore the removal of Si and P while maintaining the Fe recovery.

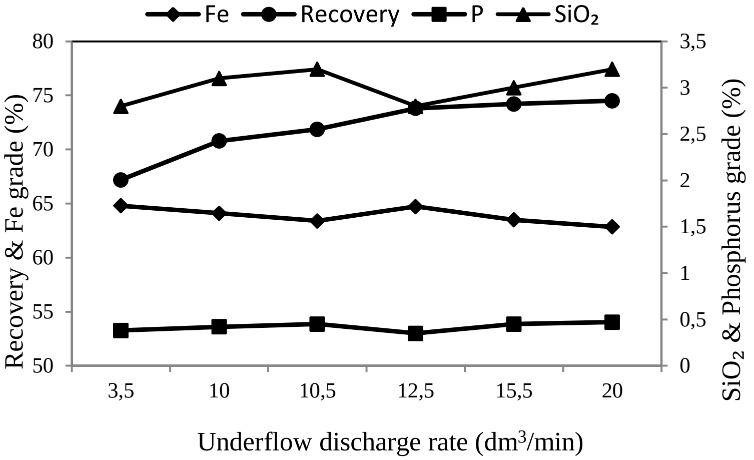

Fig. 6. Effect of underflow discharge rate on the grade and recovery of iron and grades of silica and phosphorus in the hydroseparator underflow (using Chador-malu flotation feed samples)

At a constant upward water flow, the required velocity of water flow for moving gangue particles to the overflow decreases as the underflow rate increases. In this situation, the large gangue particles, which have a high settling rate, can have the enough time for passing through the fluidized bed, and find their way to the underflow discharge (Sarkar et al., 2008). The reduction in the quality of underflow product and the increase of the weight recovery proves the validity of the argument. On the other hand, as the underflow rate decreases, the water flows towards the overflow stream. In this case, the rate of the upward current is more than the settling rate of the fine particles and as a result increases the iron content of the overflow. Based on these results (Fig. 6), it can be concluded that at an equal rates of underflow and overflow (12.5 dm^3/min), the hydroseparator will have a reasonable separation efficiency. In this case the average recovery was around 74% (with a standard deviation of 0.58) and the average grades of Fe, P, and SiO_2 were 64.72%, 0.35%, and 2.8%, respectively.

Feed well height

Table 2 shows the test results of changing the feed well height, at two levels of 10 and 17 cm, and at upward water flow rates of 12 to 45 dm^3/min. It can be seen from Table 2 that in all levels of water flow rates, the increase in the feed well height from 10 to 17 cm increased the weight recovery to the underflow.

Table 2. Effect of feed well height and upward water flow rate on performance of hydroseparator

Upward water rate (dm^3/min)	Feed well height (cm)	Recovery (%)		Fe (%)		P (%)		SiO_2 (%)	
		Test 1	Test 2	Test 1	Test 2	Test 1	Test 2	Test 1	Test 2
12	10	96.23	97.10	63.38	63.00	0.49	0.57	3.56	3.49
	17	97.18	97.67	62.89	62.79	0.51	0.56	3.45	3.45
13.5	10	89.14	90.09	63.24	63.32	0.51	0.51	3.46	3.33
	17	91.89	91.34	62.12	63.10	0.51	0.56	3.51	3.60
15	10	89.50	89.02	63.26	63.64	0.45	0.43	3.06	2.95
	17	90.34	89.90	63.28	63.30	0.46	0.45	3.12	3.20
25	10	70.27	73.73	64.46	64.12	0.44	0.43	2.91	2.91
	17	71.63	74.84	63.91	63.87	0.47	0.40	2.90	2.89
45	10	62.66	64.34	64.55	64.22	0.40	0.39	3.02	2.91
	17	64.03	65.91	64.74	64.53	0.41	0.40	3.11	2.81

When the feed well is at the lower position (17 cm), the particles have fewer opportunities to stay in the fluidized bed; therefore some of them pass through the fluidized bed toward the underflow discharge, without separation. However, when the feed well height is at higher position (10 cm), the silica and phosphorus contents of underflow are lower. In addition, when the height is 10 cm, the iron recovery in the hydroseparator product (underflow) is relatively higher. In this case, the bulk density of the fluidized bed increases, and particles settling rate decreases. Therefore the low density particles stays in the fluidized bed but the high density particles will pass through it, as a result, the iron grade of underflow will increase (Luttrellet et al., 2006; Sunilet et al., 2013).

Effect of upward water flow rate

In order to study the effect of upward water flow in hydroseparator, the experiments at 10 cm feed well height and equal overflow and underflow rates were performed (Table 2, and Figs. 7 and 8). Figure 7 shows that by increasing the water flow, in spite of better separation of phosphorus and silica from the concentrate (underflow), a significant amount of iron particles move towards the overflow, therefore reducing the recovery. At the water flow rate of 45 dm^3/min, iron recovery reached 62%. By increasing the water flow, the speed of water exceeds the settling rate of particles and large amount of particles go towards the overflow weir. The increasing the water flow rate decreased the viscosity of fluidized bed which affected the separation efficiency of hydroseparator (Tripathyet et al., 2015; Sunilet et al., 2013).

In the lowest level of water flow rate (12 dm^3/min), the highest concentrate recovery (approximately 96%) was achieved. However, in this case, the silica and phosphorus contents of the concentrate are more than required levels. Low water flow rate is unable to transfer the gangue particles to overflow and the concentration of particles in the fluidized bed will increase. In this situation, because of trapping the particles or displacing gangue particles to the underflow the quality of concentrate will decrease (Luttrell et al., 2006; Sarkar et al., 2008). By increasing the upward water rate to 15 dm^3/min, the recovery drop to 88.5%, and the content of silica and phosphorus decreased to 3.05% and 0.46%, respectively. At water flow rate more than 15 dm^3/min, larger amounts of silica and phosphorus went through the overflow, but the iron recovery in concentrate also decreased.

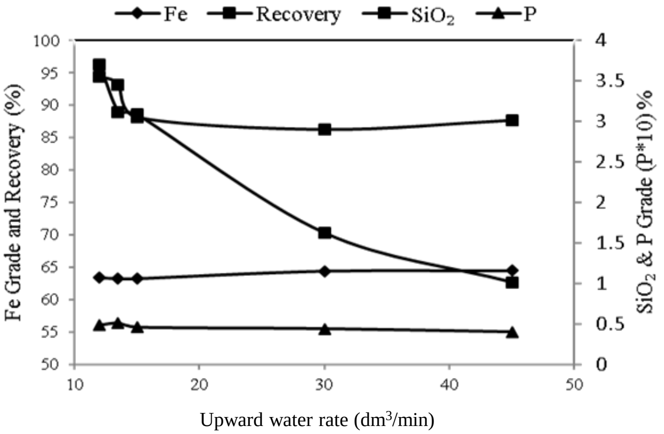

Fig. 7. Effect of water flow rate on the phosphorus, silica, and iron grades and recovery

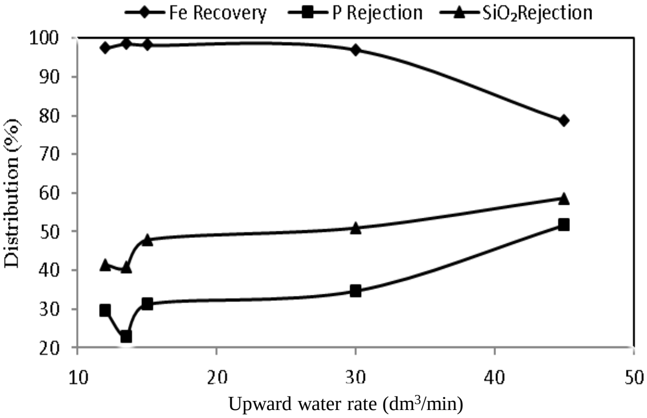

Fig. 8. Effect of water flow rate on iron recovery in underflow and distribution of silica and phosphorus in overflow

As can be seen in Fig. 8, using 15 dm^3/min of water flow rate showed better results in removing the silica and phosphorus from concentrate while maintaining the iron recovery, compared to lower water rates. The recovery of silica and phosphorus to overflow increased by increasing the water flow, and it reached up to 50%. But the recovery of iron at water flow rate of higher than 15 dm^3/min decreased from 94% to around 80%.

The distribution of silica and phosphorus in tailings (overflow) at water flow rate of 15 dm^3/min shows obvious superiority than water flow rates of 12 and 13.5 dm^3/min. In this case, the silica and phosphorus distribution in the tailings (overflow) showed an increase of 5% and 15.5%, respectively, while the iron distribution decreased around less than 1%.

After determining the suitable water flow rate, underflow rates and the feed well height, more tests at the combination of these parameters were conducted. At the water flow rate of 15 dm^3/min, the feed well height of 10 cm and equal overflow and underflow rate of 7.5 dm^3/min, the recovery of iron to underflow was around 89.5%. In this condition, the silica and phosphorus contents of the concentrate were calculated as 3% and 0.45%, respectively.

Flotation tests on hydroseparator product

Although the hydroseparator removed some parts of the impurities from the feed material, but the phosphorus and silica contents were more than the required levels. The reduction of impurities by flotation method, using the reagents of Chador-malu plant, was investigated. Alke+Dirole (fatty acid based) was used as collector, sodium silicate as iron depressant, and a mixture of sodium hydroxide and sodium carbonate as pH regulator. The results showed that it was possible to reach the iron concentrate with the silica and phosphorus contents of 2% and 0.037%, respectively. In this case, the iron grade of concentrate was 68.5%, and the total recovery was approximately 87%. The flotation test on the feed, before hydroseparator, resulted in a concentrate with higher silica and phosphorus content of 3.5% and 0.06%, respectively.

Magnetic test on feed of cleaner magnetic separator

In Chador-malu processing plant, the concentrate of first magnetic stage is reground in a ball mill, in close circuit with hydrocyclone. The overflow of hydrocyclone is sent to the cleaner magnetic circuit (Fig. 9).

Sample (case-2 in Table 1) was taken from the hydrocyclone overflow (flow number 1 in Fig. 9). Davis Tube tests on the samples showed that from this feed a concentrate with phosphorus of up to 0.14% and silica up to 0.73% could be obtained, whereas according to Fig. 8, the grade of phosphorus in the concentrate of present cleaner circuit is around 0.20%. It seems that the cleaner magnetic separators are not capable of removing the phosphorus; probably because the phosphorus is presented as fine particles of apatite in the feed of the magnetic separator.

In this section, the possibility of using hydroseparator to remove some parts of the fine gangue particles from the cleaner magnetic feed is studied. As the size and quality of the magnetic feed was similar to that of flotation feed, the optimum operational conditions of hydroseparator from the previous experiments were applied. The operational parameters were set at: water flow rate of 15 dm^3/min, feed well height at 10 cm, and equal overflow and underflow rates.

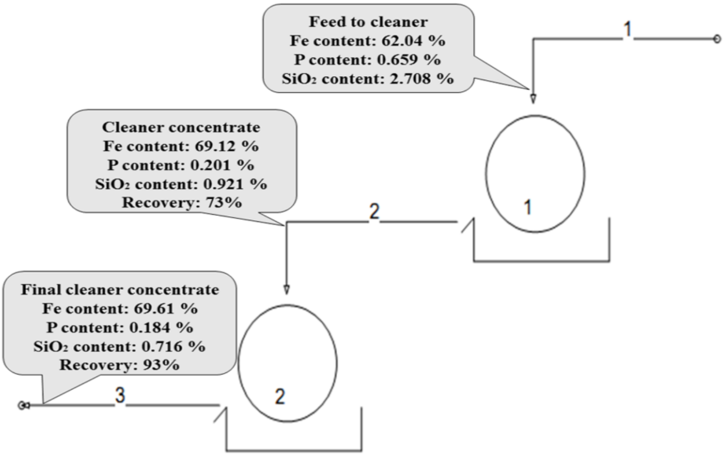

Fig. 9. Operational conditions of cleaner magnetic separators of Chador-malu processing plant

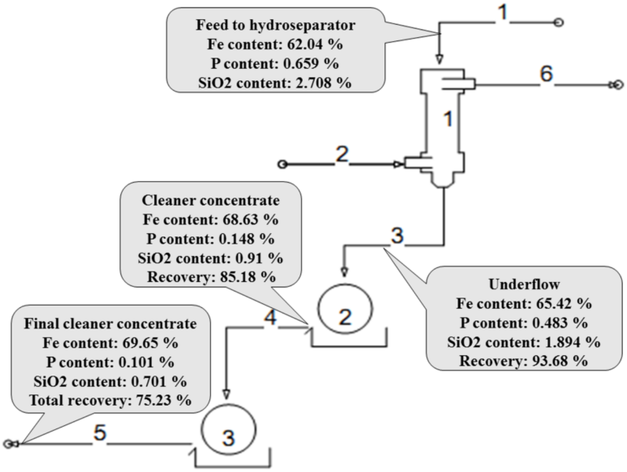

Fig. 10. Combining hydroseparator with low intensity magnetic separator
(Flow numbers 6 and 2, is the hydroseparator overflow and upward water flow, respectively)

Low intensity drum magnetic separator tests on the hydroseparator underflow of the plant magnetic feed samples, (Fig. 10) were close to the results of test on the same feed with Davis Tube. The phosphorus grade of the magnetic separation concentrate was 0.15%. It is postulated that the hyroseparator had removed the fine gangue particles from the feed, which are difficult to be removed by magnetic cleaners.

Finally, in laboratory scale, a concentrate with 75% recovery at 0.10% phosphorus was obtained.

Conclusions

In this study, the preliminary results of using a laboratory-scale hydroseparator, for removal of fine gangue particles, from the flotation and magnetic separators feed samples of Chador-malu processing plant are presented.

A considerable amount of phosphorus and silica impurities in the feed material of flotation and cleaner magnetite separation, presented in the size range of less than 25 μm, could not be effectively removed in the current plant operation.

It was shown that the feed well position, water flow rate, and discharge rate affect the separation efficiency of particles in the hydroseparator. When the feed well height was at a higher position (10 cm), the silica and phosphorus contents of the underflow were lower, and the iron recovery was relatively higher. On the other hand, by increasing the water flow rate, in spite of better separation of phosphorus and silica from the concentrate (underflow), a substantial amount of iron particles moved towards the overflow, therefore reduced the iron recovery.

The operational parameters of the hydroseparator, for effective removal of fine particles, were adjusted at water flow rate of 15 dm^3/min, the feed well height of 10 cm, and equal underflow and overflow rates. With feed samples of less than 45 μm, an iron recovery of 90% with reasonable amount of impurities was obtained.

The flotation tests on the hydroseparator underflow of flotation feed samples, showed that it was possible to obtain a concentrate with silica and phosphorus contents of less than 2% and 0.04%, respectively, whereas, the flotation test on the same feed sample, without going through the hydroseparator, produced a concentrate with silica and phosphorus content of around 3.5% and 0.06%, respectively.

Processing of the cleaner magnetic feed with the hydroseparator, and applying magnetic separation on the underflow material resulted in a high quality iron concentrate, compared to the current Chador-malu plant practice. In this case, the phosphorus content decreased from 0.66% to 0.10%, at a total iron recovery of around 76%.

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