DIRECT MEASUREMENT OF INTERNAL MATERIAL FLOW IN BENCH SCALE WET LOW-INTENSITY MAGNETIC SEPARATOR

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ABSTRACT

In mineral processing, material transport is commonly monitored between unit operations; flow rate, solids concentration, and particle size distribution of suspension flow in pipes are measured online using standard equipment. In many situations this information could be complemented by measurements inside the process equipment.

In this work a wet Low-Intensity Magnetic Separator, where no means for internal flow measurements exist today, is used to evaluate a proof of concept for an ultrasound-based measurement method. The method is utilized for direct measurements of internal suspension flows in a bench scale unit of the counter-current type. Two ultrasound transducers (2.25 MHz) form an Acoustic Backscatter System capable of monitoring flow characteristics in several positions inside the separator.

Using this method it is possible to study, e.g. the effect of slurry feed rate, slurry solids concentration, magnet assembly angle, and drum rotational speed on the internal suspension flow. The method also gives indications about material/concentrate build-up. These direct measurements can aid both in machine design and to improve process control.

1 INTRODUCTION

In mineral processing, material transport is commonly monitored between unit operations; flow rate, solids concentration, and particle size distribution of suspension flow in pipes are measured online using standard equipment. In many situations this information could be complemented or replaced by measurements inside the process equipment. Additionally the mining industry has a constant need to optimize the performance of their processes. In wet Low-Intensity Magnetic Separation (LIMS) four process parameters of major importance are; throughput, amount of gangue in the concentrate, loss of magnetic material to the tailings, and the total water usage of the process. Being able to monitor the material transport inside a separator during various operating conditions would help in optimizing these parameters. In this work internal measurements in a wet LIMS are made using an ultrasound-based method.

Wet LIMS is used to separate ferromagnetic particles from non-magnetic particles. The particles are fed to the separators in suspension with water, and the feed is separated into a thick magnetic concentrate and a dilute tailings stream. For a more detailed description see e.g. Stener (2013). Fig. 1 shows schematic drawings of three tank designs adapted from Metso (2014). The magnetic assembly has been divided into zones using the concepts of Davis and Lyman (1983), and the shaded area indicates approximate pulp level as in Forcica et al. (1958).

Fig. 1. Schematic drawings of three wet LIMS tank designs. a) Con-current type separator. b) Counter-current. c) Counter-rotation.

There are a large number of operational factors influencing magnetic separator performance. Dardis (1989) and Morgan and Bronkala (1993) describe a number of these, for example; magnetic material feed rate, feed magnetic grade, feed solids concentration, separator magnet assembly design, and separator tank design. In addition there are a number of machine settings which affect performance; pulp level in the separator, magnet assembly angle, drum-to-tank clearances, and drum rotational speed. Dardis (1989) worked with the process of dense medium recovery, which is similar to the process of magnetic separation of fine magnetite in preparation for pelletizing.

Also Lantto (1977) studied the factors affecting separation performance and found magnetic flocculation inside the separator to be the major mechanism for recovery of fine magnetite particles. Rayner and Napier-Munn (2000) saw similar effects, and concluded that to achieve efficient magnetic flocculation inside the separator the concentration of magnetic material in the feed has to be sufficiently high. According to Lantto (1977) the factor which limits capacity when working with coarser material is the solids flow rate. When working with finer material the feed needs to be diluted more, because of the greater specific surface area, and slurry flow rate becomes the capacity limiting factor.

Regarding concentrate quality, however, the misplacement of gangue particles into the concentrate tends to increase with a decrease in particle size, mainly due to entrainment of gangue in chains of ferromagnetic particles. Also, if the feed is fine enough the gangue particles tend to act as part of the fluid medium; the recovery of gangue to the concentrate becomes proportional to the recovery of water to the concentrate, Hopstock (1985). In the current work the focus lies on counter-current type magnetic separators used for cleaning of a magnetite material prepared for pelletizing, which means that the feed material is fine. Rayner and Napier-Munn (2003) also investigated the process of dense medium recovery, and propose that the mechanism controlling magnetic separator concentrate density is one of drainage.

Another factor which seems to have a strong influence on concentrate solids concentration, and as mentioned above, the concentrate quality, is the material build-up inside the separator. This material build-up is strongly affected by e.g.;

- the magnet assembly angle (controls how high the magnetic material is lifted by the magnets and the drum in the concentrate discharge; a high lift gives a more efficient material removal, and less material build-up, in the dewatering zone.)
- the drum rotational speed (faster rotation gives less time for water to drain.)
- the distance between the overflow weir and the separator drum.

To study the material separation, transport, and dewatering processes described above an Acoustic Backscatter System (ABS) is used. Two methods presented earlier by the authors are combined and evaluated in a realistic separator geometry. The first method (Stener et al., 2014a), Ultrasonic Velocity Profiling (UVP), is an ultrasound based pulse-echo method for measuring particle velocity. Using this method it is possible to measure how particle flow velocity varies with penetration depth. When applied to flows of mineral suspensions with high solids concentration, similar to those in the separators, UVP is unique in combining non-intrusive measurements, operation with access to only one side of the flow, operation in opaque

suspensions, good spatial resolution, and a fast sampling rate. In this paper, the UVP method is developed further to estimate not only particle velocity in the direction of the transducer, but particle velocity in arbitrary direction in a two-dimensional plane. This is accomplished by combining the measurements from two simultaneous UVP measurements. With the second method (Stener et al., 2014b), it was demonstrated how a short-time (windowed) Power Spectral Density estimate can be used to obtain qualitative information on local solids concentration variations. Ultrasound pulses are transmitted into the suspension, and the resulting backscatter is recorded. The statistics of the backscatter depend on solids concentration, particle size distribution, particle density, etc. If the material is not changed during the experiment, this gives a rough estimate of the local solids concentration.

Until now no means exist for internal measurements, but if the material build-up and flow patterns inside the separator can be monitored this will give new possibilities to control and develop the process of wet magnetic separation. The main purpose of this work is to study how changes to the operational conditions can be monitored in equipment handling mineral suspensions of high solids concentration, using ultrasound. A laboratory scale wet LIMS is used as a proof of concept. Information that would help in understanding the internal workings of these separators are for example; measurements of internal flow patterns (flow speed and direction) and estimates of the thickness, and thickness variation, of the magnetic layer attached to the separator drum. The interpretation of the measurements will be made in the context of wet LIMS utilized for separation of fine magnetite in the later stages of magnetic separation, where material is prepared for pelletizing.

2 METHOD

The investigation is carried out in a purpose built experimental setup. A bench scale wet LIMS is connected in a closed system with a pump and a mixer tank. The investigation is carried out as a designed experiment studying factors important to machine performance. During each run in the designed experiment, the separator is monitored with both ultrasound-based

measurements and a video camera. The ultrasound measurement system consists of two ultrasound transducers and data acquisition equipment. Two-dimensional (2D) velocity vectors are extracted from the ultrasound measurements using a cross correlation based method. Information about local solids concentration is extracted from the amplitude of the echo signal.

2.1 Experimental setup

The wet LIMS used is a SALA laboratory unit (TU-30712-16) of dimensions $\varnothing 200 \times 115$ mm fitted with a purpose built counter-current (CTC) type tank, see Fig. 2a. The main dimensions are scaled 1:6 from a full size industrial separator, the Metso $\varnothing 1200$ mm counter-current type separator. The custom made separator tank consists of walls made from a white thermoplastic, a front made from a clear polycarbonate, and a rear frame of stainless steel. The separator is connected in closed loop with a mixing tank and a pump; both the magnetic and the non-magnetic products from the separation are circulated back to the mixer, see Fig. 2b. The flow is driven by a progressing cavity pump (Netzsch NM053BY01L06B, www.netzsch.com) controlled by an AC drive (Emotron VFX48-010, www.emotron.com). The suspension temperature is stabilised by a heat exchanger fed with cold tap water. The parts are connected using rubber hosing with an internal diameter of 50 mm. To keep the sensors free from settling particles a small flow is introduced close to the transducers using a small peristaltic pump (Watson-Marlow 503S, www.watson-marlow.com). This pump is stopped momentarily during all ultrasound measurements.

Fig. 2. Experimental setup. a) Laboratory scale wet LIMS with purpose built CTC-tank. Photo captured from the feed side, before the experiments. b) System layout; separator (LIMS), mixer (M), pump (P), heat exchanger (HE), and sampling point (S). Data acquisition equipment; pulser receiver (PR), digitizer (DAQ) and computer (PC). Close up shows the four available sensor positions. In this study, positions 3 and 4 (with overlapping paths) are used.

2.2 Data acquisition

The measurements are made using two immersion transducers (Olympus V306, www.olympus-ims.com), both with a specified centre frequency of 2.25 MHz. Each transducer is controlled by one pulser-receiver (Panametrics 5800PR and 5072PR, www.olympus-ims.com). The received backscatter signal is processed by a digitizer (ADQ214, www.spdevices.com) featuring 400 MS/s at 14 bit resolution. Pulse timings are controlled by a microcontroller (Arduino Duemilanove, www.arduino.cc) running custom software. Before each ultrasound measurement the suspension temperature in the mixer is measured using a digital thermometer (ASL F250 MKII, www.aslltd.co.uk).

Each measurement is made by having one transducer transmit a short ultrasonic pulse into the flow and sample the echo from the particles. The sampling frequency is 400 MHz and the sampling duration is 80 μ s, giving a measurement depth of approx. 60 mm (depending on the suspension temperature). To capture one velocity profile using UVP, two measurements are needed; these are made at a pulse repetition frequency of 6 kHz. To get good accuracy in the

reported data 512 measurements are made during 2.56 s and combined into one velocity profile. To acquire a 2D-representation of the flow velocity two of the measurements described above are made simultaneously at two angles into the flow. To avoid interference between the transducers only one of the two transducers transmits a pulse during each measurement, but due to a limitation in the digitizer both channels are sampled simultaneously, hence half the dataset needs to be discarded during signal processing. Using this method, see Fig. 3, both transducers can be sampled in the same time span.

Fig. 3. Schematic description of data acquisition scheme and sampling times for both channels of the digitizer, one transducer is connected to each channel. High level indicates when the digitizer is sampling the transducers. Filled circles indicate when the transducers are excited.

2.3 Video recording

During each experiment a 10 s video of the material transport was captured using an industrial camera; IDS UI-3240CP (www.ids-imaging.com) with a Nikon 85 mm lens, and the separator was illuminated by a 250 W floodlight. A frame rate of 40 fps at a resolution of 1280x1024 pixels (8 bit greyscale) was used, and the exposure time was 2.3 ms. From the video recordings the actual rotational speed of the drum was calculated for each experiment.

2.4 Experimental design

The investigation is carried out as a designed experiment, a 2-level factorial design of four factors. The factors included are; feed solids concentration, feed rate, drum rotational speed, and magnetic assembly angle (Table 1).

Table 1. Factors and their target levels in the designed experiment.

Factors	Low	Centre point	High
Feed solids concentration	5 vol% solids	5 and 10 vol% solids	10 vol% solids
Drum rotational speed	50% (“1.5”)	75% (“2.25”)	100% (“3”)
Feed pump motor speed	1400 rpm	1600 rpm	1800 rpm
Magnet assembly angle	Low (-42°)	High (-36°)	High (-36°)

The target feed solids concentration is achieved by mixing dry magnetite powder with water. The magnetite material used was supplied by LKAB (www.lkab.com) from the KA1 concentrator at Kiruna, Sweden. It was sampled from the feed stream to the second stage of wet LIMS (overflow hydrocyclone). The material density is 5.0 kg/dm^3 , the mean diameter is $34 \text{ }\mu\text{m}$, and 85 wt% of the material is finer than $45 \text{ }\mu\text{m}$. The stated concentrations are checked by sampling the stream, at (S) in Fig. 2, and then drying the sample and calculating solids content. This was done three times at each solids concentration level. For the low level the solids content was 4.5% (RSD = 1.3%) and for the high level it was 9.7% (RSD = 0.6%) by volume, corresponding to 19% and 35% by mass, respectively.

The target slurry feed rate (pump motor speed) is controlled by the AC drive via MATLAB. The same samples used for calculating the feed solids concentration was also used for calculating actual slurry flow rate, by sampling the feed during a specific time period. Fig. 4 shows the measured slurry flow rate together with calculated solids feed rate. Since the drum width is

115 mm, the maximum feed rate of 2.9 kg/s/m drum length corresponds to 1200 kg/h in the test unit.

Fig. 4. Variation of feed rate with pump speed at both levels of target feed solids concentration. a) Slurry feed rate. b) Solids feed rate.

The target drum rotational speed is controlled by a mechanical lever on the driving motor, but the speed is also affected by the magnetic material loading in the separator. Therefore the rotational speed was calculated from the video footage of each experiment. On the low drum speed factor level (50%), the average speed was measured to 43 rpm (RSD = 6%), and on the high level (100%) the average speed was 74 rpm (RSD = 8%), corresponding to a peripheral speed of the drum of 0.45 m/s and 0.77 m/s respectively.

The target magnet assembly angle is controlled by a mechanical lever on the separator, and can be adjusted between two fixed angles. The position of the magnetic pole closest to the concentrate discharge was determined using a steel blade, see Fig. 5. A change in magnetic assembly angle of 6° corresponds to 10 mm on the $\varnothing 200$ drum circumference. All experiments with their measured levels have been compiled in Table 2.

Fig. 5. Position of the magnetic pole by the concentrate discharge, determined using a steel blade. a) Low setting. b) High setting.

Table 2. Calculated factor levels for all $2^4 = 16$ runs and the 6 centre runs. All low factor levels are shaded. Calculated solids and water feed rates are added for reference.

Exp. No.	Drum Speed [rpm]	Feed rate [dm ³ /min]	Magnet angle [°]	Conc. [vol%]	Solids feed rate [kg/min]	Water feed rate [kg/min]
1	45.2	19.0	-42	4.53%	4.4	18.1
2	79.8	19.0	-42	4.53%	4.4	18.1
3	42.9	42.2	-42	4.53%	9.5	40.3
4	74.2	42.2	-42	4.53%	9.5	40.3
5	47.7	19.0	-36	4.53%	4.4	18.1
6	82.9	19.0	-36	4.53%	4.4	18.1
7	45.2	42.2	-36	4.53%	9.5	40.3
8	83.1	42.2	-36	4.53%	9.5	40.3
9	41.3	18.9	-42	9.72%	9.2	17.0
10	65.0	18.9	-42	9.72%	9.2	17.0
11	39.8	41.5	-42	9.72%	20.1	37.5
12	63.2	41.5	-42	9.72%	20.1	37.5
13	40.9	18.9	-36	9.72%	9.2	17.0
14	71.2	18.9	-36	9.72%	9.2	17.0
15	40.9	41.5	-36	9.72%	20.1	37.5
16	69.7	41.5	-36	9.72%	20.1	37.5
Center p.	52.7	30.5	-36	4.53%	6.9	29.1
Center p.	60.8	30.5	-36	4.53%	6.9	29.1
Center p.	59.5	30.5	-36	4.53%	6.9	29.1
Center p.	49.8	29.9	-36	9.72%	14.5	27.0
Center p.	52.1	29.9	-36	9.72%	14.5	27.0
Center p.	52.9	29.9	-36	9.72%	14.5	27.0

2.5 Signal processing

The local particle velocity (v) in the direction of the transducer is calculated using UVP. Details on the method can be found in Stener et al. (2014a). The spatial coordinates of the measurements are calculated using the known sensor position together with the acquisition times and speed of sound in water at the measured temperature. The particle velocity vector ($\mathbf{v}$) in the direction of the transducer ($\hat{d}$) is then calculated as $\mathbf{v} = v\hat{d}$.

The velocity vector ($\mathbf{v}$) is calculated for both channel A and B, each positioning a plane in 3D-velocity space, see Fig. 6. By assuming that the flow velocity perpendicular to both measurements is zero a third plane is generated. The combined velocity ($\mathbf{v}_c$) is calculated as the intersection between these three planes. For the final results, the measurement position ($\mathbf{p}$) is put in the middle between the two original measurement positions. The two measurements are aligned using the point where they intersect (see the close up in Fig. 2b) as a reference.

Fig. 6. Description of the method used to combine channel A and B velocity measurements into a single velocity vector (compare to Fig. 8b). Velocity is defined positive when particles are moving towards the transducer.

3 RESULTS

Particle velocity and concentration measurements are made on the concentrate side of a laboratory scale wet LIMS. The ultrasound measurements are complemented with video footage through the transparent wall of the separator tank. Parameters important to operating conditions have been varied in a designed experiment. The effects of varying different parameters are described below.

3.1 Effect of solids concentration and feed rate

In the concentrate discharge an increase in feed solids concentration has similar impact to an increase in feed rate; the amount solid feed increases. However, when the feed rate is increased also the water feed increases, though most of the water never reaches the monitored zone. When more material is fed into the separator than the drum is able to remove, this results in material build-up inside the separator. This material build-up prevents particle movement in the monitored zone, which generally results in lower measured particle velocities, Fig. 7 shows one example.

Fig. 7. Particle flow velocity patterns comparing the effect of feed solids concentration at; medium feed rate, medium drum speed, and high magnet assembly angle.

3.2 Effect of water feed rate

By comparing experiments where the feed solids concentration was low and the feed rate was high with experiments where the solids concentration was high and the feed rate was low, the impact of changing the feed dilution can be estimated. These combinations are used as two levels of water feed rate. The high level of water feed rate corresponds to a flow rate approximately twice as fast compared to the low level. In the measurement zone this results in similar flow patterns, but the flow velocities are higher when the water feed is high, see Fig. 8. However, the material build-up in the dewatering zone is much larger with the low water feed. This could imply that additional dilution water helps to give the magnetic material an efficient transport through the separator, and that more dilution water in the feed adds capacity for solids feed.

Fig. 8. Particle flow velocity patterns comparing the effect of water feed rate at; high drum speed and high magnet assembly angle. a) High solids concentration together with low feed rate gives low water feed. b) Low solids concentration together with high feed rate gives high water feed.

3.3 Effect of drum speed

Using a high drum speed increases the capacity of magnetic material removal from the dewatering zone, but it also brings more water (and fine gangue) to the concentrate. High drum

speed also creates high recirculating flow in the measurement zone. In the measured flow patterns this has the effect that changing drum speed from low to high reverses the direction of flow in most cases. An example of this is shown in Fig. 9.

Fig. 9. Particle flow velocity patterns comparing the effect of feed solids concentration at; low solids concentration, low feed rate, and high magnet assembly angle.

3.4 Effect of magnet assembly angle

The magnet assembly angle determines how high the magnetic material is lifted by the drum. With a high magnet assembly angle the magnet field fades out higher up (10 mm) in the dewatering zone. With the magnet assembly in its high position the measured particle flow generally has the same direction, but the flow speed is faster compared to the low position. Fig. 10a-b shows a typical example. The impact on the flow patterns is similar to that of increased solids feed rate. The impact of higher lift of the magnetic build-up can also be seen on the video footage, Fig. 10c-d.

Fig. 10. Particle flow velocity patterns and photographs from the side of the separator, comparing the effect of magnet assembly angle at; low solids concentration, low feed rate, and high drum speed.

3.5 Backscatter strength

The strength of the measured echo gives information about the material build-up on the drum surface in the measurement zone, see Fig. 11. Since the same data is used for these results, as for the flow patterns above, the measurements are made in the same area in the separator, see Fig. 2. When the transmitted ultrasound pulse reaches the build-up of magnetic material the backscattered amplitude increases temporarily, due to the increased acoustic impedance of the suspension. But due to the high signal attenuation in the high solids concentration build-up the pulse is also attenuated fast. The dashed lines in Fig. 11 highlight the transition to a zone of increased solids concentration, created by the magnetic build-up on the separator drum.

When using the low level of feed solids concentration (4.5 vol%), two experiments show a strong material build-up in the measurement zone; when the feed rate is high and the drum speed is low, see Fig. 11a-b. This is also the levels expected to give the highest solids build-up. At the high feed solids concentration (9.7 vol%), only two experiments have a measurement zone not filled with solid material. This is when the feed rate is low and the magnet assembly angle is high, see Fig. 11c-d. In Fig. 11d the measurement time of 2.6 s corresponds to 3.0 drum revolutions.

Fig. 11. Backscatter strength varying with distance from the tank bottom, and time. The distance from tank bottom is defined in the direction of the transducers; 30 mm corresponds to the approximate position of the drum surface.

3.6 Repeatability

Three measurements made at different times, all settings are at the same levels, and the same feed material was used. Fig. 12 shows that the measurement method has sufficient repeatability.

Fig. 12. The same experiment repeated thrice, indicating good repeatability. Levels used are low feed solids concentration and the remaining factors at their centre level.

4 DISCUSSION

Comparing the experiments presented in this paper to the previous work in the rectangular duct (Stener et al. 2014a), a number of major differences were noted. In the rectangular duct the flow was turbulent and the solids concentration was relatively homogeneous throughout the flow. Therefore, the signal attenuation was strong throughout the flow. In the bench scale LIMS the solids concentration has strong gradients; close to the drum it is very high (probably around 35 vol% solids) but through most of the measurement path the solids concentration is low. This makes measurements in the interesting part of the flow easier. The rest, the thick cake on attached to the drum can be assumed to follow the drum rotation. The geometry of the separator, on the other hand, is more challenging, since no main flow direction can be assumed and since there is limited space to fit the transducers.

To estimate material build-up, the backscattered signal amplitude is used. Even though the amplitude has no direct relation to local particle concentrations, it is still useful for detecting material build-up. In the presented conditions this method has proven to be competent at assessing the internal material flows. Also repeatability between measurements appears to be sufficient, probably due to the fact that each pattern uses data from 512 profiles measured over a timespan corresponding to a few drum rotations.

Since the video recordings only capture the material flow and build-up towards one of the tank walls, there is a risk of wall effects. In this small separator the feed is evenly distributed over the full width of the tank, so if the edge effects appear to be small and the results are representative of the internal flow and material build-up. In a full scale separator, however, the slurry feed duct is centred towards the middle of the drum, which probably leads to significant edge effects.

The highest solids feed rate levels (high feed solids concentration together with high slurry feed rate) was chosen to mimic material overload conditions in the separator. This was achieved, and the video footage show significant material build-up for all combinations where feed solids concentration and slurry feed rate are high. The level of solids feed ($20 \text{ kg/min} = 10 \text{ tonnes/h/m drum}$) is indeed high and can be compared to the typical feed to a $\varnothing 600 \text{ mm}$ separator of approx. $11 \text{ tonnes/h/m drum}$ (Sundberg, 1998). The actual separation result was not the subject of study in these experiments.

5 CONCLUSIONS

Using the described Acoustic Backscatter System it is possible to detect the presence of recirculating flows of non-magnetic particles leaving the concentrate stream. A high flow rate in this zone is likely to give a cleaner concentrate.

With this system it is also possible to monitor the amount of material build-up on the concentrate side of the separator. Keeping a balanced material loading in the separator dewatering zone is important to separator performance; too low material loading in the dewatering zone is likely to give low throughput, low solids concentration in the concentrate, and a less clean concentrate. Overloading, on the other hand, is likely to prevent washing of the concentrate, thus also leading to a less clean concentrate.

In the future the methods should also be tested in larger magnetic separators, pilot or full scale. The larger internal distances could affect the performance of these methods in several ways. For

example a larger measurement depth will cause more signal attenuation. In a larger separator, where there is more space for the transducers, the method should also be applicable in other parts of the tank, to monitor for example properties of the tailings stream.

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