Minerals Engineering 62 (2014) 2–8

Contents lists available at ScienceDirect

Minerals Engineering

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

Evaluation of the applicability of ultrasonic velocity profiling in conditions related to wet low intensity magnetic separation

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ARTICLE INFO

Article history:
Available online 18 September 2013

Keywords:
Iron ore
Magnetic separation
Process instrumentation
On-line analysis
Fine particle processing

ABSTRACT

The internal material transport and selection processes of the wet low-intensity magnetic separators (LIMS) are poorly understood; this calls for improved measurement techniques. In this work an ultrasonic velocity profiling (UVP) technique for measuring how material flow velocity varies with penetration depth is presented. A measurement depth of just a couple of centimetres would greatly improve the understanding of the separation process in a LIMS.

When applied to flows of mineral suspensions with high volumetric solids concentration, similar to those in the separators, UVP is unique in combining:

- Non-intrusive measurements.
- Operates using just one sensor element (transducer).
- Relatively good spatial resolution.
- Penetrates opaque suspensions.
- Fast sampling rate.

Here, flows are studied in a rectangular duct (50 × 75 mm). Using magnetite suspensions, measurement through the whole depth of 50 mm is made with good accuracy. Velocity profiles are presented for solids concentrations of 5% and 9% solids by volume (20% and 36% by weight). Even at 9 vol% solids it is possible to reach a penetration depth of more than 25 mm.

1. Introduction

The wet low-intensity magnetic separator (LIMS) is the workhorse for winning of fine ferromagnetic particles from ore pulps; despite this the internal workings of the machine are poorly understood. Also, as experienced by the industry, when pushed to higher capacities and with higher concentrate quality demands, it has started to show some limitations. To increase the understanding of this problem the use of computer simulations were attempted by Lejon Isaksson (2008). One conclusion was that trustworthy simulations need measurements for validation. The maximum depth of a full size separator tank is about 100 mm, but to verify simulations a measurement depth of just a couple of centimetres would suffice.

1.1. Magnetic separation

The wet LIMS (Fig. 1) consists of a rotating non-magnetic drum with a number of internally fixed magnets arranged with alternating polarity. The rotating shell is partially submerged in a tank into which the suspension of ferromagnetic material is fed. The magnetic portion of the feed material is attracted towards the drum surface and then carried through the alternating magnetic field and out through the concentrate discharge. The history and physics of wet LIMS is described in more detail by Parker (1977).

The amount of research done on wet LIMS is limited, but some has been published, for example Lantto (1977a,b) investigated how various factors influenced the performance of wet LIMS for a titaniferrous magnetite ore. Some of the factors investigated were the number of separation stages, the magnet assembly design, tank design, pulp density and magnetic flocculation. It was found that magnetic flocculation had central significance for determining the separation result. Rayner and Napier-Munn (2003) combined empirical advice and experimental trials to develop process models for wet drum magnetic separators. Also here, magnetic flocculation was shown to play a central role. A model to predict loss of magnetic material was presented where the loss depended upon a first order flocculation rate and the residence time within the separation zone. Even though this work was aimed at wet drum magnetic separators used for dense medium recovery, much of the theory should also be applicable to concentration of magnetite.

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0892-6875/$ - see front matter
http://dx.doi.org/10.1016/j.mineng.2013.08.005

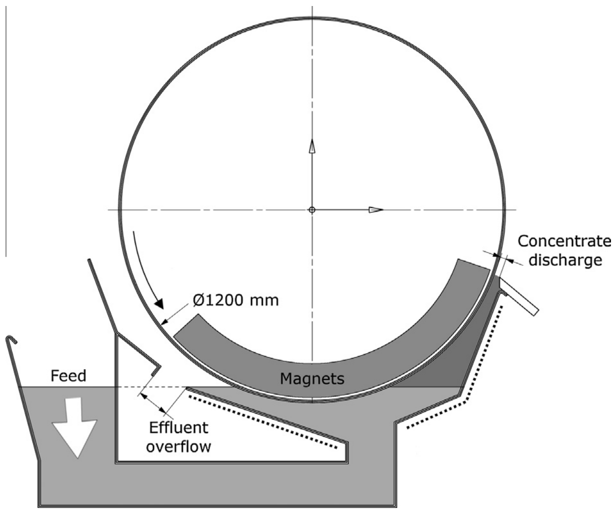

Fig. 1. Cross section of wet LIMS of counter-current type (design by Metso, www.metso.com). Dotted lines indicate walls of special interest for mounting of sensor for flow velocity measurements.

Recently Dworzanowski (2010) described, from a general point of view, how the various designs and operating variables interact, how they affect performance and also provides guidelines on operation. Factors given high importance included tank design, magnet assembly configuration, feed preparation, feed rate, level control and drum/tank distance.

Generally, one of the challenges of optimizing LIMS is the balance between attracting too much material, and thus getting mixed grains of low grade in the concentrate, and attracting too little material and losing the very fine (liberated) magnetic fraction to the tailings. This is where understanding the limitations of LIMS and the mass transfer of material within a LIMS could help in circuit configuration and processing to maximize the overall magnetite recovery.

To gain a deeper understanding of the process of wet LIMS, measurements of internal particle flow are needed. To obtain good quality data the following specification was set up:

1. The sensor is required to operate from one direction only, this since the separator design allows physical access to the flow from only one side (dashed lines in Fig. 1).
2. A technique capable of penetrating an opaque and attenuating suspension is required.
3. Some degree of spatial resolution is needed to interpret the results.
4. A non-intrusive technique is preferred since the best results are obtained if the flow is not disturbed. Also the internal environment could be very harsh on equipment.
5. Information about both flow speed and suspension concentration variations is desired.

2. Method

To meet the specifications listed above an ultrasonic flow velocity measurement method was chosen. These techniques are (almost) non-invasive quantitative techniques capable of operating in opaque fluids. There are three main categories of ultrasonic flow velocity measurement methods; transit time, Doppler-based and speckle correlation techniques. Most of these methods originate from the field of medicine or navigation but have in more recent years found many other applications. Hein and O'Brien (1993) made a review summarizing these developments.

In transit-time flow measurement systems two ultrasonic transducers operate by alternately transmitting and receiving bursts of sound energy between them. The difference in measured transit time is directly proportional to the velocity of the liquid in the pipe. Transit-time techniques measure the bulk flow velocity. However, transit-time techniques cannot be used in the current target application since they require sensors on two sides of the flow.

Ultrasonic Doppler flow meters employ the frequency shift (Doppler Effect) of an ultrasonic signal when it is reflected by suspended particles or gas bubbles in motion. Doppler based methods measure the motion of the particles. This technique is used for example by Takeda (1986), Wiklund and Stading (2008), Chemloul et al. (2009) and Hunter et al. (2011).

Speckle correlation techniques track the movement of particles or local density variations in a suspension. A visualization of particle distribution in turbulent suspension flows can be found in Wood et al. (2005). Short ultrasonic pulses are generated and these create backscatter waves, which are sampled and run through a cross-correlation process to extract a time delay. From this delay the particle displacement and velocity can be calculated. This technique is computationally demanding, but since the generally available computing power increases, this limitation rapidly diminishes. Already Dotti et al. (1976) used an ultrasonic cross-correlation technique to measure blood flow.

Related methods include the use of arrays of sensors to acquire a 2D profile; cf. Sandrin et al. (2001), Manneville et al. (2001) and Carlson and Ing (2002), and the use of similar (or the same) equipment to measure slurry density and solids concentration; cf. Bamberger and Greenwood (2004) and Furlan et al. (2012).

2.1. Ultrasonic velocity profiling

To develop a method capable of operating in the demanding environment of a wet LIMS tank a variant of the speckle correlation technique was selected. The method, here called ultrasonic velocity profiling (UVP), uses an ultrasound transducer to track particle motion in the flow. The transducer first transmits a short pulse and is then used as a receiver to record the backscattered signal (echo). This backscattered signal contains information about the particles in the flow.

By acquiring two backscatter signals closely spaced in time and then cross-correlating them it is possible to follow the movement of particles. By dividing the backscatter signals into short segments and cross-correlating them piecewise it is possible to obtain information on how this movement varies with position. The distance travelled by the particles are related to the time delay (lag) corresponding to the strongest correlation. Since the time between the two backscatter signals is known it is possible to calculate particle velocity. The transducer inclination angle (θ) is used to project the measurements on the direction of flow. The method is described in more detail in the signal processing section.

During signal processing it is assumed that the volume responsible for measured backscatters at each time, the interaction volume (IV), is of negligible size. In reality the volume is finite. Jorgensen et al. (1973) describe the IV as flat drop shape, but here it is sufficient to treat the IV as a flat cylinder, see Fig. 2. Close to the transducer the diameter of the IV (d) is assumed to be identical to the transducer diameter and the diameter then increases as the pulse diverges (with divergence angle α). The height (h) of the IV is related to the pulse duration and the speed of sound. Note that the interaction volume is a theoretical concept, in reality there is no distinctly defined border between affected and unaffected suspension.

Due to the finite volume of the IV, velocity profiles measured using UVP can become distorted in the vicinity of channel walls. With the current setup approximately 5 mm from each wall is

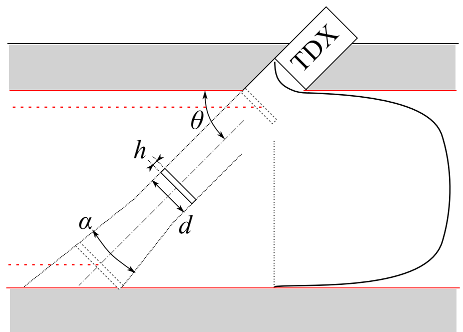

Fig. 2. Ultrasonic pulse path and the concept of interaction volume. In the vicinity of duct walls (marked with dashed lines) the measurements will be affected by wall interaction effects. A typical turbulent flow velocity profile is included to the right.

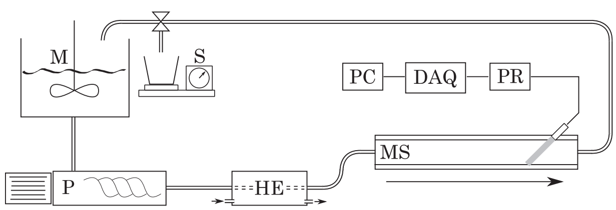

Fig. 3. Experimental setup comprising mixer (M), pump (P), heat exchanger (HE), measurement section (MS). Also sampling position (S) and data acquisition equipment is shown; pulser–receiver (PR), digitizer (DAQ) and computer (PC).

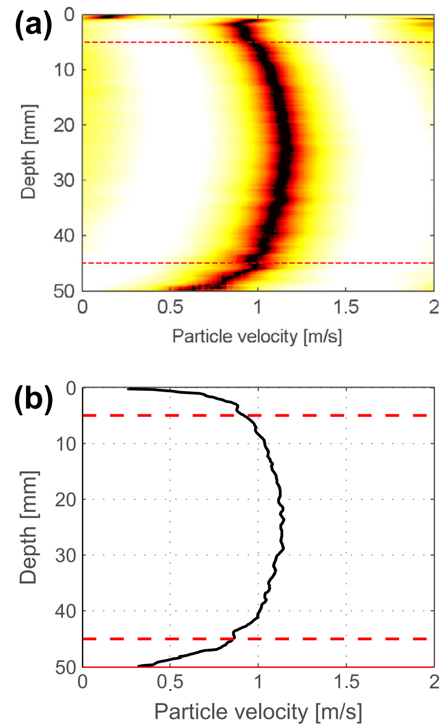

Fig. 4. (a) Cross-correlation strength, coloring indicates how the correlation strength between the two windows ($x1$ and $x2$) varies with lag (m) and vertical position. Dark colors indicate strong correlation. (b) Corresponding flow velocity profile calculated as the velocity corresponding to the strongest correlation at each depth. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

affected. For the top wall (transducer side) this means that the flow might be underestimated since the IV is only partly in the main flow. For the bottom side this means that a signal reflected twice from the bottom wall influences the measurement. To some extent it would be possible to compensate for these effects during signal processing, but this was not done in these experiments.

2.2. Experimental setup

The proposed method is developed and evaluated using the experimental setup in Fig. 3. The flow is driven by a progressing cavity pump (Netzsch NM053BY01L06B, www.netzsch.com) capable of supplying up to 14 m^3/h. This corresponds to an average flow velocity of up to 1 m/s in the measurement section. The pump motor is controlled with an AC drive (Emotron VFX48-010, www.emotron.com) and the suspension temperature is stabilised at 25–30 °C by a heat exchanger

Table 1
Ultrasonic transducers (Olympus, www.olympus-ims.com).

Manufacturer-specified centre frequency (MHz)	Approximate wavelength (mm)	Divergence half angle	Near field (mm)	Part No.
1.0	1.50	8.1°	27	V303
2.25	0.67	3.6°	61	V306
3.5	0.43	2.3°	94	V382
5.0	0.30	1.6°	135	V309

Table 2
Experimental parameters used.

Property	Settings I[a]	Settings II[b]	Equation
Vertical measurement duct depth	50 mm	50 mm	
Transducer inclination angle (θ)	45°	45°	
Transducer nominal diameter (d)	∅13 mm	∅13 mm	
Sample frequency (f_s)	400 MHz	200 MHz	
Pulse repetition frequency ($1/T_{PRF}$)	5 kHz	8 kHz	
Measurements per flow profile (O)	200	200	
Window length (M)	1000	1000	
Vertical spatial resolution (Δy)	2.7 µm	5.3 µm	Eq. (2)
Horizontal velocity resolution (Δv)	13 mm/s	42 mm/s	Eq. (5)
Sound velocity in suspension (c)[c]	1480–1510 m/s	1480–1510 m/s	

[a] Used in Fig. 5a and b.
[b] Used in Fig. 5c–f.
[c] Depending on suspension temperature.

fed with cold tap water. The parts are connected in closed loop using rubber hosing with an internal diameter of 50 mm.

The walls of the measurement section (MS) (depth 50 mm, width 75 mm and length 1 m) are made from 12 mm clear polycarbonate and the ultrasonic transducer is fitted at a 45° inclination in one end of the section. The length of straight duct in front of the transducer is 0.85 m, corresponding to 14 hydraulic diameters. To evacuate entrained air from the recess by to the transducer a small peristaltic pump (Watson-Marlow 503S, www.watson-marlow.com) is used. The flow rate (through a ∅1.5 mm hole) is negligible compared to the main flow.

2.3. Material and suspension properties

The magnetite material (approx. 69% Fe) used was supplied by LKAB (www.lkab.com) from the KA1 concentrator at Kiruna, Sweden. It was sampled from the feed stream (overflow hydrocyclone) to the second stage of wet LIMS. The material density is 5.0 kg/dm^3, as measured with a pycnometer (Micromeritics 1305, www.micromeritics.com). Particle size analysis by laser diffraction (Cilas 1064, www.cilas.com) showed that the mean diameter is 34 μm and mechanical sieving showed that approx. 85 wt% of the material is finer than 45 μm.

The dry magnetite powder is mixed with water to reach desired concentrations. The stated concentrations are checked by sampling the stream, at (S) in Fig. 3, and then drying the sample and calculating solids content. To avoid sedimentation a bulk flow velocity in both the hoses and the measurement section of 0.75 m/s or higher is used during all experiments.

2.4. Electronic equipment

The measurements are made using the immersion transducers listed in Table 1. These are managed by a computer controlled

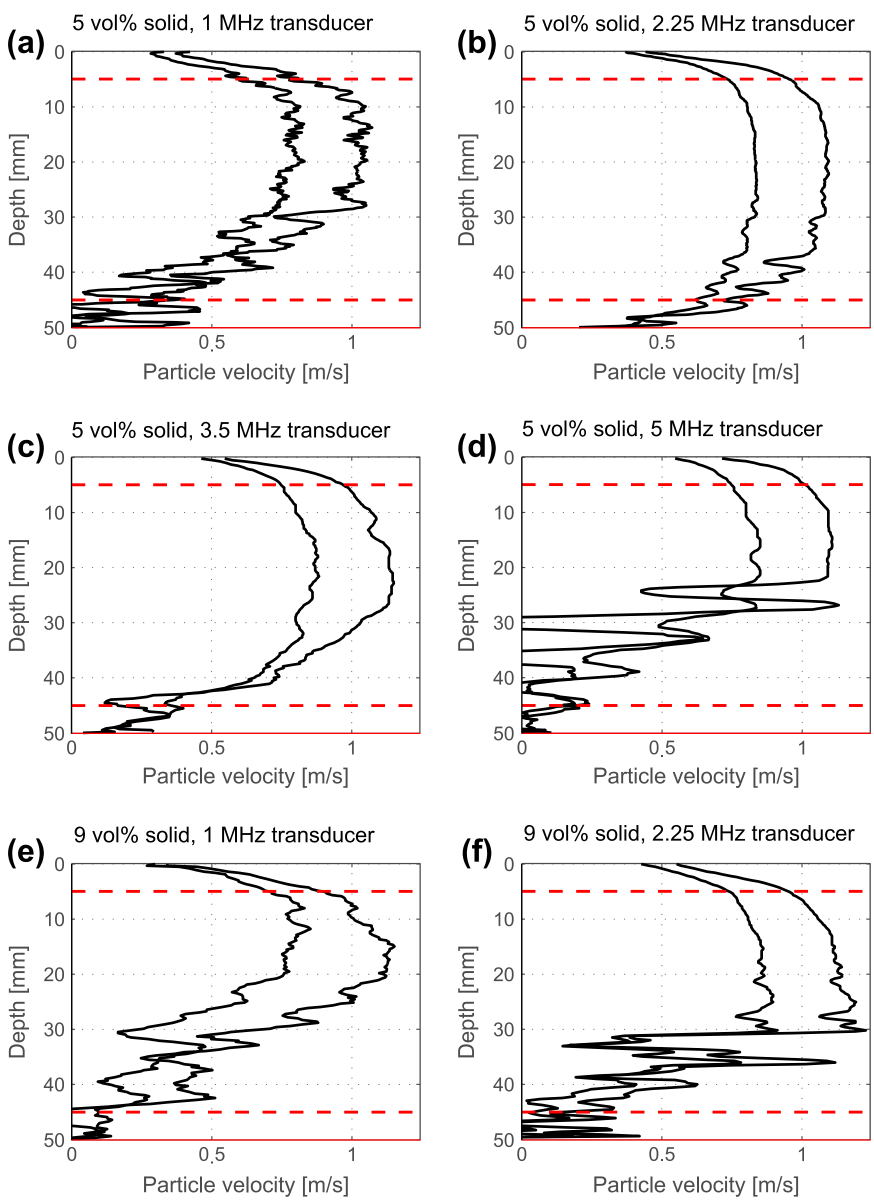

Fig. 5. Measurements on flow of magnetite suspension at bulk flow speed of 0.75 and 1 m/s. Two different concentrations and four different transducers are compared. The transducer is placed above the figures. 0 and 50 mm on the vertical axis represent the top respective bottom of the measurement duct. The dashed (red) lines mark areas where wall effects might influence the measurements (See Fig. 2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pulser–receiver (Panametrics 5800PR, 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. Before each ultrasonic measurement the suspension temperature in the mixer (M) is measured using a digital thermometer (ASL F250 MKII, www.aslltd.co.uk).

2.5. Signal processing

Signal acquisition control and signal processing is carried out in MATLAB (www.mathworks.com) running custom code. Related properties are listed in Table 2. Assume that two backscatter signals (echoes), $p_1[n]$ and $p_2[n]$ are acquired by sampling the received analogue signals at a sampling rate $T_s = 1/f_s$ so that,

$$p_i[n] = p_1(nT_s), \quad i = 1,2, \quad n = 1,2,\ldots,N \tag{1}$$

The vertical spatial distance between each sample $p_i[n]$ is calculated using the vertical spatial resolution

$$\Delta y = \frac{T_s c}{2\cos\theta} \tag{2}$$

where c is the speed of sound in the medium (calculated using measured temperature and standard data for water). θ is the angle between the ultrasonic transducer and the direction of flow (see Fig. 2). The resolution is divided by a factor 2 since the pulse travels back and forth through the suspension.

The two signals are acquired at a pulse-repetition frequency (PRF) so that the time between the two acquisitions is $T_{\mathrm{PRF}} = 1/\mathrm{PRF}$. If the PRF is sufficiently high, we can assume that the particles in the interaction volume (IV) has translated like an entity, so that the backscatter signatures differ only by a time delay (n_0) proportional to the movement of the suspension during the time T_{PRF}.

The time for a pulse to travel from the transducer to a particular IV and back varies only with the position of the IV, this means that each sample (n) will carry information from different depth in the flow. By dividing the sampled signal into short segments,

$$\begin{aligned} x_1[k] &= \{p_1[1+k],\ p_1[2+k],\ldots,\ p_1[M+k]\} \\ x_2[k] &= \{p_2[1+k],\ p_2[2+k],\ldots,\ p_2[M+k]\} \end{aligned} \tag{3}$$

the displacement of the flow can be calculated as a function of depth. The windows are M samples long taken from $p_1[n]$ and $p_2[n]$, respectively, and window index k = 0, 1, ..., N-M-1.

The first step towards finding this time delay between each of these windows is to do a cross correlation of the two windows

$$XC[m,k] = \sum_{k=0}^{N-M-1} p_1[n]p_2[n-m] \tag{4}$$

where m is a sufficiently large span of lags; e.g. m = −256, −255, ..., 0, ..., 255, 256.

The horizontal flow speed corresponding to a certain lag m is calculated using the horizontal flow velocity resolution

$$\Delta v = \frac{T_s c}{2\sin\theta} \cdot \frac{1}{T_{\mathrm{PRF}}} \tag{5}$$

Fig. 4a shows the cross-correlation strength (XC) as a function of windows index converted to depth (using Eq. (2)) and lags converted to flow velocity (using Eq. (5)). The final particle flow velocity profile in Fig. 4b has been estimated by finding the flow speed corresponding to the maximum correlation strength.

To obtain better estimates of the particle velocity profiles, the above procedure was repeated 200 times, each resulting in an estimated velocity profile. For each depth the median flow velocity is calculated; the median is known to be good at suppressing outliers, meaning that this should also efficiently discard estimates where the two signals have de-correlated. After median filtering all flow profiles have been filtered with a moving average smoothing filter:

$$v_s[k] = \frac{1}{2N+1}\left(v\left[k-\frac{N}{2}\right] + v\left[k-\frac{N}{2}+1\right] + \ldots + v\left[k+\frac{N}{2}\right]\right) \tag{6}$$

3. Results

At solids concentrations of 2 vol% or lower, the UVP technique is capable of measuring through the whole available depth of 50 mm. In Fig. 5a–d the suspension has a solids concentration of about 4.7 vol%, corresponding to 20 wt%. Under these conditions the 2.25 MHz transducer produces the most reliable results. A higher transmitting frequency makes the signal attenuate faster, and in this case it does not penetrate the full 50 mm, instead about 25 mm is reached for the 3.5 MHz transducer and 20 mm for the 5 MHz transducer.

In the combination of particle size distribution, solids concentration and flow conditions used in this work, the pulses from the 1 MHz transducer does not interact strongly enough with the suspension flow to create a high contrast backscatter signal. This results in increased uncertainty in the flow velocity profile estimation.

When the concentration is increased to 9 vol% (33 wt%), in Fig. 5e–f, the 2.25 MHz transducer still produces the most reliable results and it is possible to reach a depth of almost 30 mm. In the

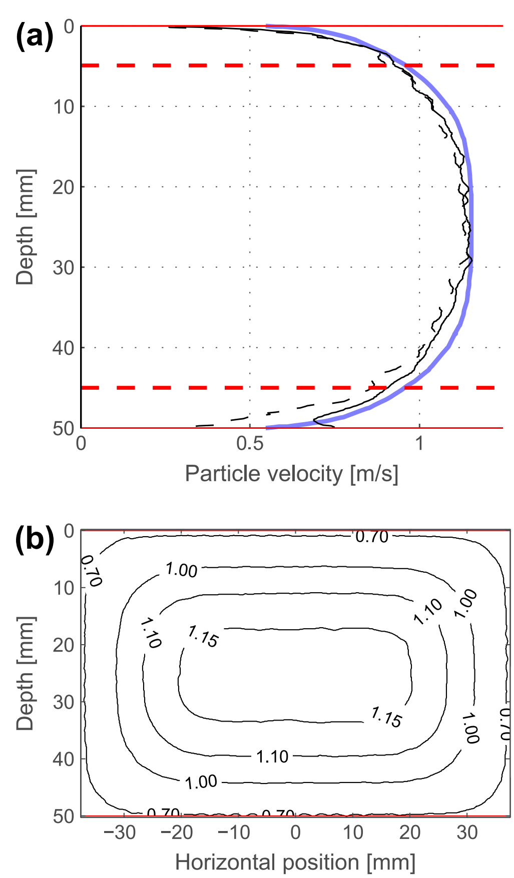

Fig. 6. (a) CFD simulation of water (▬) compared to measured particle velocity profiles (bulk flow speed 1 m/s) where suspensions with low solid content is used; (- -) <0.5 vol% solids and (—) approximately 2 vol% solids. (b) 2D cross-section from CFD simulation showing velocity contours (m/s).

Table 3
Ultrasonic flow profiles in literature.

Reference	Solid material	Avg. particle dia.	Max. solids conc.	Max. penetration depth (transducer inclination angle)	Transducer centre frequency (MHz)	Transducer size (mm)
Takeda (1986)	Al_2O_3	5 μm	Low	∅12 mm (60°)	4.2	∅4
Carlson and Ing (2002)	Magnetite	54 μm	Low	∅34 mm (45°)	3.5	0.4[b]
Wiklund and Stading (2008)	Mineral	11–90 μm	20 wt%	∅36 mm (~70°)	2–4	∅5,10
Chemloul et al. (2009)	Glass	270 μm	2 vol%	∅20 mm (67°)	8	∅2
Hunter et al. (2011)	Glass	10 μm	5 wt%	300 mm (0°[a])	1	∅15
Kotzé et al. (2013)	Kaolin	N/A	17 vol%	∅16 mm (70°)	4	∅8

[a] Sedimenting particles.
[b] Pitch of 64 element transducer.

proposed application this distance would be sufficient to cover a large portion of the wet LIMS tank volume.

As a comparison, and check-up on the measurements, basic computational fluid dynamics (CFD) simulations (Fig. 6) have been carried out in Comsol Multiphysics 4.3 (www.comsol.com). The model consists of a duct with the same dimensions as the measurement duct where water (at 20 °C) flows with an average velocity of 1.0 m/s. The software-generated "physics controlled" mesh consists of 535×10^3 elements. The k–ε turbulence model is used and all other settings are left at their defaults. It was found that the measurements were in good agreement with the simulation.

4. Discussion

For low solids concentration, where interparticle scattering can be neglected, the penetration depth of an ultrasonic pulse is mainly dependent upon ultrasound frequency (quadratic dependency), particle radius (cubic dependency) and fraction of solids (linear dependency) (Carlson, 2010). For solids concentration above approximately 0.1 vol% solids (Hunter et al., 2012) interparticle scattering can no longer be neglected. Still the signal attenuation can be assumed to increase with increasing ultrasound frequency, decreasing particle size and increasing solids concentration.

To improve penetration depth for a given suspension flow the ultrasonic transducer centre frequency can be tweaked for each application to reach optimal performance. Also the vertical penetration depth can be improved by increasing the transducer inclination angle (θ), though this will come on the expense of reduced measurement accuracy and robustness. Using an inclination angle of 70° instead of 45° would shorten the pulse path by 25% for the same penetration depth. Another factor to consider is the main excitation of the transducer. In the current setup the pulser–receiver generates a negative impulse (−300 V) with pulse energy of 100 μJ. According to specification the transducers can handle stronger excitation, which might yield improved penetration depth.

When comparing the presented results to those in the literature (Table 3) both deeper measurements, and measurements in thicker suspensions can be found, but not both at the same time. Also some of these measurements use transducers on two opposite sides of the flow, which effectively cuts the ultrasonic path length in half.

In these experiments, and also in the proposed application, a turbulent flow is required to keep the dense particles in suspension. This means that, on a small length scale the fluid flow can have any direction because of turbulent vortices. The time to complete 200 repeated measurements is in the order of 100 ms. Also the portion of the flow being considered in each velocity calculation depends on the shape of the interaction volume. The strongest backscatters have the most influence on the measurements, and particles from a span in depth of up to approximately 11 mm could influence one single point on the velocity profile. These factors make it difficult to differentiate between measurement fluctuations caused by turbulence and fluctuations being measurement error.

Also the estimation of the speed of sound in the suspension affects the measurement accuracy. In Fig. 5 the speed of sound is assumed to be the same as for water of the same temperature. The speed of sound in water at 20 °C and 30 °C is 1482 m/s and 1509 m/s respectively. But the speed of sound also depends on solids concentration and particle size distribution. For example Wiklund and Stading (2008) uses a value of 1530 m/s for mineral slurry at 20 °C. Since the measured flow speed depends linearly on the estimation of speed of sound the practical effect is small; for instance, the error resulting from using 1482 m/s instead of 1530 m/s is only 3%.

5. Conclusions

It is possible to get good qualitative measurements in demanding environments and since just one sensor is needed setup and signal acquisition can be simple. Also no calibration is needed; measured velocity depends only on the speed of sound in the suspension. As shown here, the technique can operate up to at least 9 vol% (36% by weight) solids concentration and down to very dilute suspensions; only a small amount of particles is required to create echoes.

The penetration depth depends strongly on the volume fraction of solid material, but to be able to measure particle flow velocity only a short distance inside a process unit could yield a much deeper understanding of the behavior of the LIMS unit process. In these experiments the 2.25 MHz transducer produces the most reliable results. At 2, 5 and 9 vol% solids concentration the vertical penetration depth is 50, 35 and 25 mm respectively at a 45° transducer inclination angle. This technique has great potential in the field of minerals engineering, wherever there is a need to measure mineral suspension flow in narrow channels.

Acknowledgements

Financial support to the project WET LIMS – Measurements and models, by the Hjalmar Lundbohm Research Centre (HLRC), is gratefully acknowledged. Practical support from LKAB personnel in plant sampling is greatly appreciated.

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