WET LOW-INTENSITY MAGNETIC SEPARATION:
MEASUREMENT METHODS AND MODELLING

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Cover illustrations: Magnetite in magnetic field (top), cross section of a wet low-intensity magnetic separator (middle-left), sensor holders with mounted transducers and ultrasound wave paths (middle-right), measured flow velocity pattern (bottom-left), measured power spectral density (bottom-centre), and modelled magnetic particle capture (bottom-right).
In the mining industry, ferromagnetic particles (e.g. magnetite) are concentrated using wet low-intensity magnetic separation (LIMS). Mineral particles in suspension with water are pumped into the separator tank, and a magnetic concentrate is extracted by use of magnetic forces. The performance of the process is to a large extent controlled by the internal flow conditions in the separator, governed by process and machine settings. Due to the machine design these settings are not independent, and in some cases it can be difficult to reach optimal process performance. The main purpose of this work has been to find a measurement method capable of monitoring internal material transport in the wet LIMS, and use these data, together with numerical flow modelling, to get an increased understanding about the separation process.

Since the mineral slurry entering the separator is essentially opaque, and the solids concentration is rather high, an ultrasound-based method was selected for the internal measurements. It is of interest to monitor both the internal flow patterns, as well as material build-up resulting from the magnetic field. The method development and evaluation proceeded in steps with increasing complexity, with later stages building on experience from the former. Initial measurements were done in model systems with simple geometries, and over a range of flow velocities corresponding to flow velocities in full-scale magnetic separators. Additional measurements were done on model systems under influence of a magnetic field of varying strength. After the measurement methods were verified in controlled laboratory conditions they were evaluated in real world conditions; \textit{in-situ} at the LKAB pilot plant in Malmberget, Sweden.

For the pilot scale experiments a setup with two ultrasound transducers, mounted at the bottom of the separator tank, was used. The factors included in the designed experiment were the feed solids concentration, drum rotational speed, position of the concentrate weir, and the magnet assembly angle. Based on this investigation the drum rotational speed was the factor having the strongest influence on the overall flow velocity in the dewatering zone. Also, the presence of a recirculating flow transporting gangue particles away from the concentrate was confirmed. The factor with strongest influence on this flow is also the drum rotational speed, together with the magnet assembly angle. Using this method it is possible make high quality measurements of internal flow velocity profiles. It is also possible to monitor material build-up on the separator drum, and e.g. detect overload of magnetic material.

The ultrasound based measurement system resulting from this work measures particle velocity based on a cross-correlation principle. Two consecutive ultrasound pulse-
echo signals are cross-correlated piece-wise, to obtain a local velocity estimate. By measuring the suspension flow from two directions, using two transducers, 2D velocity vectors can be estimated. Using the same measured data, but instead studying how the spectral contents of the signal vary with axial distance from the transducer, a qualitative measure of variations in local solids concentration can be obtained.

During this work several aspects of wet LIMS have been studied, with focus on the internal material transport processes inside the separators. State-of-the-art measurement methods have been utilized to monitor the material flow inside the separators. Particle capture and entrainment have been studied on the particle level using numerical flow modelling. Measurement results have been linked to operational conditions of the separators. The insights gained, and the methods developed, have generated new possibilities to control, optimise, and develop the wet LIMS process.

**Keywords:** Wet low-intensity magnetic separation, magnetite beneficiation, in-line process monitoring, pulse-echo ultrasound, ultrasonic velocity profiling, solids concentration, signal processing, windowed cross-correlation, power spectral density, numerical flow modelling.
The work presented in this thesis has been carried out mainly at the Luleå University of Technology (LTU) in northern Sweden, at the Mineral Processing group within the division of Minerals and Metallurgical Engineering. The work has been done in collaboration with the mining company Luossavaara-Kiirunavaara AB (LKAB) with founding from the Hjalmar Lundbohm Research Centre (HLRC).

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Starting with my master thesis project I also got involved in another interesting research project, on mill modelling. For this I thank Pär Jonsén, and co-authors Hans-Åke Häggblad and Kent Tano.

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**Paper VII:**
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Licentiate thesis

**Ultrasonic flow measurement methods applicable to wet low intensity magnetic separation**
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CONTENTS

Part I 1

Chapter 1 - Introduction
1 Wet low-intensity magnetic separation 3
2 Measurement methods 4
3 Modelling 5
4 Research background 6
5 Research scope and method 7

Chapter 2 - Background
1 Ferromagnetic suspensions in magnetic fields 9
2 Wet LIMS for magnetite concentration 18
3 Ultrasound and flow measurement methods 24

Chapter 3 - Method
1 Experimental setups 33
2 Materials 35
3 Ultrasound data acquisition 36
4 Signal processing 38
5 Experiments 41

Chapter 4 - Results and discussion
1 Measurements in undisturbed flow in the flow cell (Paper I, II, VII) 50
2 Measurements in settling suspension in the flow cell (Paper III, VII) 52
3 Measurements and simulation of magnetic particle capture (Paper V, VII) 54
4 Measurements in the bench scale wet LIMS (Paper IV) 59
5 Measurements in the pilot scale wet LIMS (Paper VI, VII) 61

Chapter 5 - Conclusions
1 Ultrasound based measurement methods in wet LIMS 67
2 Material transport inside wet LIMS 68
3 Industrial relevance 69

Chapter 6 - Future work 73
References 75
Part II

Paper I
Paper II
Paper III
Paper IV
Paper V
Paper VI
Paper VII
Part I
Wet low-intensity magnetic separation (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. In the mining industry, wet LIMS is used to concentrate ferromagnetic ores, e.g.; magnetite, taconite, and some pyrrhotite ores. In beneficiation of magnetite ores, wet LIMS is the standard equipment when the material top-size has been reduced below 10 mm. The process is also used to recover magnetic medium in dense medium separation plants (Bronkala et al., 1985).

A typical magnetite concentration circuit involves several stages of magnetic separation, and magnetic separation is commonly alternated with grinding, see Figure 1. Separators are mounted in units having from one to four drums in a single separator unit. Ideally, all particles are liberated, and all ferromagnetic particles together with a small portion of the water end up in the concentrate and all non-magnetic particles together with most of the water ends up in the tailings. The separation is based on differences in magnetic properties of the separated materials.

A wet LIMS consists of three main parts; the rotating drum, the static magnet assembly, and the tank. The non-magnetic cylindrical drum (typically of stainless steel with rubber lining) contains a number of fixed magnets. The drum is partially submerged in a tank into which the ore pulp is fed. The ferromagnetic fraction is pulled towards the drum surface, carried across the magnetic poles, and removed from the tank (Parker, 1977). Wet LIMS are available with several tank designs, several drum diameters, and several magnet assembly configurations. Today, the standard drum is ø1200 mm, older installations use smaller drums, and drums of ø1500 mm have been tested during the 1980’s, see Sundberg (1998).
During operation a number of machine settings (see Figure 2) and feed properties can be adjusted independently, e.g.; the magnet assembly distance, overflow weir distance, suspension feed rate, feed solids concentration, drum rotational speed, and the scavenger zone depth. Separator design and operation are covered in more detail in section 2 of chapter 2, and by e.g. Lantto (1977a, b), Sealy and Howell (1977), Hopstock (1985), Dardis (1989), Morgan and Bronkala (1993), Sundberg (1998) and Rayner and Napier-Munn (2000, 2003a, b).

Figure 2. Schematic drawings of a typical counter-current type wet LIMS.

2 Measurement methods

The measurement methods available for studying wet LIMS can be divided into in-line flow measurements, manual stream sampling, and manual measurement of machine properties. Prior to this work there were no internal flow measurement results published in the literature, neither were there tailored methods available for that type of measurements.

Material transport is commonly monitored between unit operations in a concentrator; the flow rate, solids concentration, and the particle size distribution of suspension flow in pipes can be measured in-line using standard equipment. However, when more detailed information is needed the streams have to be sampled manually. A range of methods are available for analysis of stream samples, e.g.; sizing by laser diffraction, chemical analysis by x-ray fluorescence (XRF), magnetic content analysis by Satmagan or Davis Tube, and phase identification by x-ray diffraction (XRD). After sieving the samples, these analyses can be complemented by e.g.; optical microscopy, XRF by size, scanning electron microscopy (SEM), and liberation analysis based on SEM-data.

When interested in separator performance the sample analysis can be complemented with machine specific measurements, e.g.; measuring the magnetic field strength of the separator magnet assembly using a magnetometer, measuring the flow rate of dilution water to the individual separators, determining the position of the magnet assembly, and measuring the overflow weir distance (Eriksson, 2013).
3 Modelling

The models available in the literature regarding wet LIMS are mostly empirical models based on data from plant sampling. There are also a few numerical models created for studying internal flow. A number of such examples are discussed in the sections below.

3.1 Empirical modelling

Davis and Lyman (1983) studied wet LIMS used for recovery of magnetite in dense medium circuits. They modelled the relationship between concentrate solids concentration, volumetric feed rate, and separator drum speed. Also the relationship between magnetite recovery, dry feed rate, and separator drum speed was investigated. Notably, they found a linear dependency between dry magnetite feed rate and the drum speed maximizing the magnetite recovery (an increased drum speed is needed to handle an increase in dry feed rate). Furthermore, the solids concentration in the concentrate was found to decrease with increased drum speed.

Rayner and Napier-Munn (2003a) studied the same type of process. They developed a semi-empirical model for the estimation of the solids concentration in the separator concentrate. The solids concentration is modelled based on initial moisture content and a drainage rate. The initial moisture content was found to depend mainly on the drum diameter, drum rotational speed, and the volumetric feed rate. The drainage rate was found to depend mainly on the drum diameter, drum rotational speed, volumetric feed rate, and the concentrate overflow weir distance. Rayner and Napier-Munn (2003b) developed a model estimating the magnetic recovery to concentrate. The recovery was modelled based on a flocculation process; all particles not flocculated were considered lost. Fitting the model to a large dataset, the flocculation rate was found to depend mainly on the material volume susceptibility, drum diameter, drum rotational speed, and the volumetric feed rate.

A major difference for the wet LIMS process, when used for recovery of dense medium compared to concentration of magnetite ore, are issues related to liberation. When LIMS is used for dense medium recovery, the main objectives are to maximize the recovery and the concentrate density. When concentrating magnetite ore, on the other hand, a minor loss of magnetite (locked in gangue particles) is desired. Ersayin (2004) developed a model based on a pseudo-liberation concept, which could be used when liberation information is not available. The liberation state was instead approximated based on the feed grade. The empirical model estimates a relationship between the feed grade, particle size, and the magnetite recovery. Modelling was based on data sampled from three plants, and covered cobbers, roughers and finishers.

Parian (2015) also studied concentration of magnetite ore, and developed a semi-empirical model of wet LIMS used for magnetite concentration. The sample data were gathered through a survey in a concentrator at the LKAB in Kiruna, Sweden. The process model considers both particle and liberation effects. Entrainment of gangue particles are modelled based on particle size and particle recovery is modelled based on
the magnetic volume of the particle. The model can forecast the behaviour of a feed material on the particle level, e.g. relating the recovery to concentrate of mixed particles to the volumetric grade, and a particle size range.

3.2. Numerical flow modelling

Only a few numerical models of the wet LIMS are published in the literature. This is likely due to the physical complexity of the process, arising from the combined effects of magnetic, hydrodynamic, and friction forces. Also the huge range of length-scales relevant to separator performance makes modelling a challenge. The diameter of a full scale drum is in the 1 m range, and the magnetic inclusion in a mixed particle can be less than 10 µm.

One attempt at modelling the internal flow in a wet LIMS was made by Lejon Isaksson (2008), where a two-dimensional (2D) computational fluid dynamics (CFD) model of a wet LIMS was built in COMSOL Multiphysics. In that work turbulent fluid flow was simulated in geometry corresponding to a wet LIMS. The fluids used were air, water and a liquid with properties corresponding to a relevant magnetite suspension.

Murariu (2013) created a multi-physics model for simulating a wet LIMS. The model uses the discrete element method (DEM) for modelling the mineral particles. The suspension flow patterns in the separator tank are modelled using CFD and the drag force on individual DEM particles are calculated. The magnetic field intensity and gradient are determined using a finite element method (FEM), and are used to calculate the magnetic forces acting on the magnetized DEM particles. Flocculation effects are also taken into account when the inter-particle interaction forces are computed. Despite being the state-of-art in modelling of internal flows in wet LIMS, this model has some notable drawbacks. Mainly it lacks back-coupling, from DEM to CFD and from DEM to FEM; the particles do not affect the fluid flow, and neither do the magnetized particles affect the magnetic field.

4 Research background

The mining industry has a constant need to optimize the performance of their processes. In wet LIMS four factors 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. A number of physical phenomena compete in determining the outcome of the separation process, including; magnetic interaction, mechanical friction, hydrodynamic drag, and gravity. Since also strong magnetic flocculation effects need to be considered this internal material transport process becomes complex, and the flow conditions vary considerable with changes in operational conditions. Most magnetic separators used today were developed during the 1960’s, and no radical development has taken place since, Sundberg (1998). Since then there has been a lot of progress regarding tools available for the optimisation of machine and processes design. Using modern tools like e.g. multi-phase CFD simulation there should be room for improvements.
One major concern was, however, the complete lack of internal measurements, and that there are no methods available to the industry for doing internal measurements in wet LIMS. One important conclusion from the work done by Lejon Isaksson (2008) was that separator flow models, to be trustworthy, need measurements for validation. Without the measurements the separators are literally black boxes.

Another important parameter is that the cost of implementation. In recent years the cost of sensors, data acquisition equipment, and computing power has decreased considerably. Today it could be feasible to equip some, or all, separators in a concentrator with advanced instrumentation for internal measurements.

5 Research scope and method

The main purpose of this work has been to study the internal material transport processes within a wet LIMS, and also to investigate to what extent flow measurement methods can be utilized to monitor this material transport. Desired information is e.g. measurements of flow and density profiles. It is also of importance to link the measurements to the operational conditions of the separators, and that the measurements can give new possibilities to control, optimise, and develop the wet LIMS process. Another aim has been to use experience from the experimental work, together with the available literature, to understand the physical principles governing the separation result. The ultimate goal has been to create a basis for establishing improved guidelines for separator operation and understanding the source of problems observed in the industry.

The methods used include state-of-the-art flow measurement techniques, computational flow modelling, and a literature study. For the flow measurements a suitable method was selected and adapted to the conditions present in a wet LIMS under typical operating conditions; narrow geometries, opaque suspensions, and high concentration of ferromagnetic particles. The method development and evaluation proceeded in steps with increasing complexity, with later stages building on experience from the former. Initial measurements were done in model systems with simple geometries, and over a range of flow velocities corresponding to flow velocities in full-scale magnetic separators. Additional measurements were made in simplified systems under the influence of magnetic fields of varying strength. The next experimental stage was carried out in a purpose-built test rig equipped with a scaled-down version of a full-scale geometry. The final stage included pilot scale work; after the measurement methods were verified in controlled laboratory conditions they were evaluated in real world conditions. Here, statistically planned research was carried out, investigating the effects of factors important to separator performance, e.g.; the flow velocity, feed solids concentration, and the magnet assembly position.

Regarding modelling, empirical models from the literature are used as a source of information about the process, and numerical flow modelling was used to model suspension flow in simplified conditions related to wet LIMS. The numerical simulations
were set up to qualitatively correspond to the experimental work using the flow cell. Here the purpose was to gain a first indication to what extent entrainment of gangue particles contribute to the contamination of the concentrates.

The research is limited in scope, in terms of the experimental work being made in the context of wet LIMS used for separation of magnetite ore in the later stages of magnetic separation, where material is prepared for pelletizing. This implies e.g.; a fine particle size, a relatively high grade feed material, and a mineralogical composition similar to what is had in LKAB ores.
CHAPTER 2 - BACKGROUND

This chapter aims at summarizing the relevant theory on a level of detail appropriate to the following chapters. It is divided into three parts; the first part describes the physics related to flow of suspensions of fine magnetite particles in water. The second part describes wet magnetic separation in general and also some aspects of the wet low-intensity magnetic drum separators. The third part overviews the theory regarding flow measurements in suspensions using backscattered ultrasound.

1 Ferromagnetic suspensions in magnetic fields

Wet LIMS is used to separate particles in suspensions into two products, ferromagnetic particles in one product, and non-magnetic particles in the other. Separation is based on the physical properties of the particles, thus an understanding of the underlying physics is important, e.g. the influence of suspension solids concentration, magnetic ordering, and magnetic flocculation of particles. Focus is on particle sizes finer than 0.5 mm.

1.1 Aqueous suspensions of fine particles

In wet magnetic separation the feed material is mixed with water; the wet process eliminates problems associated with fine dust and also simplifies transportation. The solids concentration of suspensions is usually, for convenience, calculated by weight. However, when dealing with particle interactions and propagation of sound the corresponding volumetric concentration is more meaningful. In Figure 3 the relationship between volumetric and mass solids concentration is plotted for a particle density of 5 kg/dm³. The maximum solids concentration, for e.g. settled particles, is affected by the particle size distribution and shape. For ferromagnetic particles, in e.g. settling, filtration, and similar processes, also the level of magnetization affects the achievable solids concentration, see Eichholz et al. (2012).

1.2 Turbulent flow

Turbulence is a flow regime characterized by chaotic property changes, e.g. rapid variation of pressure and velocity in space and time. The mean flow velocity profile has a controlled shape, but locally and for short periods of time the direction of flow can have any direction and a large variation in magnitude.
Wet low-intensity magnetic separation: Measurement methods and modelling

Figure 3. Relation between volumetric and mass solids concentration, calculated for a solids density of 5.0 kg/dm³ and liquid density of 1.0 kg/dm³ (water). * Salmi (1985). ** Rayner and Napier-Munn (2003a). *** Eichholz et al. (2012).

Turbulence can be described by the Navier-Stokes equations. However, due to the wide range of mixing-length scales involved in turbulent flow, it is extremely difficult to find a numerical solution to the equations for turbulent flow. When modelling suspensions it gets increasingly difficult with increasing solids content, and such models usually need to be calibrated against experiments (Southard, 2006). For well-defined single phase fluids there are good models, see e.g. Figure 4. In a), a typical mean turbulent fluid flow velocity profile is shown. In b) the corresponding distribution of streamwise velocity fluctuations are included. The definition of mean velocity and the root mean square (RMS) of velocity fluctuations are included in c).

Figure 4. Turbulent flow a) Mean streamwise velocity distribution ($U$) along wall bisector, comparing models and experimental data at similar Reynolds numbers. b) Distribution of RMS streamwise velocity fluctuations ($u_{ RMS}$), after Breuer and Rodi (1994). c) Explanation of the mean velocity and $u_{ RMS}$, after Southard (2006).
1.3. Magnetic ordering

The magnetic properties of materials originate from the motion of electrons and the spin of the electrons and the nuclei in the atoms. All materials have magnetic moments, but it is the ordering of the magnetic moments that control the net magnetization. The materials will always strive to minimize their magnetic potential energy; this means e.g. that the magnetic moments in a particle will be ordered to minimize the net magnetization of the material. In most materials the magnetic moments are free to align in various directions to create very low net magnetization. In this text these materials will be referred to as non-magnetic.

Exceptions exist where the structure and composition of molecules and crystal lattices forces the magnetic moments to align. Figure 5 shows four types of strong magnetic ordering. A material is considered true ferromagnetic if all of its magnetic moments add a positive contribution to the net magnetization (of each domain). If some part of the magnetic moments are aligned, but antiparallel, then the material is ferrimagnetic. If the parallel and antiparallel moments balance out completely then the material is antiferromagnetic, and the material will have a zero net magnetization. Generally ferromagnetic materials have the strongest saturation magnetization and ferrimagnetic materials have the second strongest saturation magnetization. When magnetic materials are discussed more generally the term ferromagnetic is often used referring to all materials exhibiting spontaneous magnetization (Svoboda, 2004).

![Figure 5. Four types of strong magnetic ordering, with arrows indicating the strength and alignment of magnetic moments, after Svoboda (2004). Examples of a material belonging to each class (at temperatures relevant to wet processing) are also included.]

1.4. Magnetic domains

A magnetic domain is a volume of homogeneous magnetization. Without any external magnetic field the magnetic ordering inside a particle will only be homogeneous if the particle is very small; only magnetite particles smaller than 0.1 µm are normally single-domain particles, see Dunlop (1990). Larger magnetite particles will consist of more than one magnetic domain. The shape and number of magnetic domains are generally not fixed, but depends on the current external magnetic field together with the magnetic history of the particle. As with magnetic ordering the system will strive to minimize it magnetic potential energy. Domains primarily form as a balance between a minimal net magnetization and a minimal internal domain wall area. This leads to the creation of ordered magnetic domains and a small net magnetization of the particle, see Figure 6.
Wet low-intensity magnetic separation: Measurement methods and modelling

Figure 6. Three magnetic domain structures, both external field strength and domain walls add to the total magnetic potential energy. Depending on e.g. the particle size, defects, and impurities, any of the three states could correspond to a minima in potential energy.

When particles are exposed to external fields, domains with magnetization parallel to the external field begin to grow, on the expense of other domains, see Figure 7. If the external field is strong enough the particle magnetization will become homogeneous, this is called magnetic saturation. Even when the external magnetic field is removed the particle will not become completely demagnetized, this is called remnant magnetization, Lantto (1977b).

*Pseudo-single-domain* particles are particles too large to have only one domain, but show high values of remnant magnetization typical of single domain particles. Limited size (< 20 µm), geometric properties, and defects common in natural materials will prevent these particles from reaching zero net magnetization. Larger particles means increased freedom to form domains, and domains can form patterns giving the particle very low net magnetization (Hopstock, 2000).

![Diagram](image)

Figure 6. Three magnetic domain structures, both external field strength and domain walls add to the total magnetic potential energy. Depending on e.g. the particle size, defects, and impurities, any of the three states could correspond to a minima in potential energy.

Defects, such as inclusions, voids, dislocations, grain boundaries, and surface flaws are common in natural minerals. The defects provide energy barriers that pin the domain
walls and require strong reverse magnetic fields to move them to locations which result in zero net magnetization of the particle. In theory this limits both the minimum and the maximum magnetization compared to large ideal crystals. In practise very fine magnetite is impossible to demagnetize completely and the saturation magnetization will differ between samples (Hopstock, 2000).

1.5. **Magnetism and magnetic potential energy**

Calculating the attractive or repulsive force between two magnetic materials is, in the general case, a complex operation. The force depends on the shape, magnetization, orientation, and separation of the magnetic particles, together with the surrounding materials. However, by applying some approximations at least some general trends can be calculated.

The magnetic field strength ($H$), magnetic flux density ($B$), and the material magnetization ($M$), see Table 1, are related as:

$$ B = \mu_0 (H + M) \Leftrightarrow H = \frac{B}{\mu_0} - M_s $$  \hspace{1cm} (1)

where $\mu_0$ is the permeability of free space (Nordling and Österman, 2006). In vacuum $M = 0$ and Eq. (1) reduces to:

$$ B = \mu_0 H $$ \hspace{1cm} (2)

Eq. (2) can also be used to convert between field strength and flux density in vacuum.

In Figure 8 a typical hysteresis loop for natural magnetite is shown. Magnetite is typically saturated by 300–500 mT and the saturation magnetization of magnetite at room temperature ranges from 550 mT to 610 mT, see Svoboda (2004).

![Figure 8. A major hysteresis loop for a natural magnetite powder with a particle size of 5 µm (100 kA/m corresponds to 126 mT in vacuum), after Hopstock (2000).](image-url)
Table 1. Magnetic quantities and their corresponding symbols and units.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>SI unit</th>
<th>Alt. unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic flux density</td>
<td>$B$</td>
<td>T (Tesla)</td>
<td>Wb / m$^2$</td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>$H$</td>
<td>A/m</td>
<td>A·m$^2$/m$^3$</td>
</tr>
<tr>
<td>Magnetization</td>
<td>$M$</td>
<td>A/m</td>
<td>A·m$^2$/m$^3$</td>
</tr>
<tr>
<td>Permeability of free space</td>
<td>$\mu_0$</td>
<td>V·s/(A·m)</td>
<td></td>
</tr>
<tr>
<td>Magnetic dipole moment</td>
<td>$m$</td>
<td>A·m$^2$</td>
<td></td>
</tr>
</tbody>
</table>

All magnetized material in a magnetic field possesses some potential magnetic energy, and all systems strive to minimize this energy. The total potential energy ($U$) in a system can be calculated as:

$$U = \frac{1}{2} \mathbf{m} \cdot \mathbf{B}. \quad (3)$$

For a small volume of ferromagnetic material a reasonable approximation is to treat it as a magnetic dipole, see King (2012). For a magnetic dipole of a volume ($V$), or a particle of volume ($V$), having average magnetization $M$ the magnetic moment ($m$) is:

$$m = MV. \quad (4)$$

In an external field the potential energy ($U_m$) of such a dipole can be calculated as (Nordling and Österman, 2006);

$$U_m = -m \cdot B = -mB \cos \alpha, \quad (5)$$

where $\alpha$ is the angle between the two fields $m$ and $B$.

If the magnetic potential energy of a system can be decreased by rotating or moving a particle, then the magnetic field will impose a torque and/or a force on that particle. As can be seen from Eq. (5) the potential energy of the system is minimized when the two fields are aligned ($\cos \alpha = 1$, see also Figure 9c). The minimization of potential energy results in a torque ($\tau$) striving to align the magnetization of the particle with the ambient field. The torque can be calculated as the cross-product between the particle and field magnetization (Nordling and Österman, 2006), as;

$$\tau = m \times B. \quad (6)$$

As long as the particle magnetization is perpendicular to the magnetic field there will be no translating force on the particle. However, if the particle is free to rotate, it will align with the surrounding field and then start to move in the direction of increasing magnetic field strength. If the external magnetic field is homogeneous the particle will still rotate, but not translate, since the translating force is related to the magnetic field gradient, as;

$$F = \nabla (m \cdot B). \quad (7)$$

Figure 9 gives a simplified description of how a small magnetized particle (dipole) is affected by an ambient magnetic field (produced by a large fixed permanent magnet). If the particle magnetization is anti-aligned to the surrounding magnetic field, as in
Figure 9a, the particle will experience a net repulsive force and a net torque. If the particle magnetization is perpendicular to the surrounding magnetic field, as in b), the particle will be affected by a net torque but no net force. These effects will, if possible, align the particle field with the surrounding magnetic field. When the fields are aligned, as in c), the particle will experience a net force in the direction of increasing field strength.

Figure 9. Forces on a small magnetic dipole in a magnetic field if the dipole is, a) antiparallel to the field, b) perpendicular to field, and c) parallel to external field.

1.6. Suspension magnetization

Particles in suspension can easily move and rotate relative to each other and to an external magnetic field. As discussed above, the magnetization in a particle strive to align with the surrounding field. In suspensions of ferromagnetic particles there are several ways the particle magnetization can align with the surrounding field:

- Domain structure change, domains aligned with the external field grow
- Rotation, particles rotate to align magnetization with the ambient field
- Group rotation, groups of particles align with the external magnetic field.

Particles are affected by the ambient magnetic field, but the particles also affect the magnetic field. When a ferromagnetic particle is introduced in a homogeneous magnetic field the particle will distort (concentrate) the magnetic field, King (2012). This can also be seen from Eq. (1); flux density increase with increasing material magnetization for a constant magnetic field strength.

1.7. Magnetic flocculation

For suspensions of ferromagnetic particles in water, magnetic flux density is higher in the particles, compared to the surrounding medium. This creates gradients in the field, and as discussed above, gradients attract ferromagnetic particle. This particle concentration
creates even stronger gradients in the field and even more concentration. In effect ferromagnetic particles chain together and form flocs or clusters. This is called magnetic flocculation. Magnetic flocculation can be visualized, see Figure 10, by introducing ferromagnetic particles mixed with water in a magnetic field. The formation of elongated flocs can be associated to the occurrence of a number of physical phenomena, e.g.; the local magnetic force, the viscous forces and the three-dimensional thinning effects, see Chen et al. (2009).

![Figure 10. Example of magnetic flocculation, a formation of ⌀25 mm created by a concentrated magnetic pole behind the centre of the image. The material is ground magnetite particles (80 wt% finer than 45 µm) in water.](image)

Magnetic flocculation effects make particles travel in complex paths; moving in the direction where the local magnetic field increases the most. The magnetic particle-particle interaction force is a short range force, since it is inversely proportional to the particle-particle distance cubed, Murariu (2013). Svoboda (2004) describes three stages of magnetic flocculation, and whichever is active is determined mainly by the surrounding magnetic field strength and the local solids concentration:

1. At a relatively low magnetic field strength the particles are flocculated in a controlled manner. The degree of flocculation is controlled by a balance between the magnetic force and other competing forces. In this stage flocculation is selective and mostly ferromagnetic particles are captured. Field strength between 8 mT and 80 mT can be sufficient to initiate magnetic flocculation.
2. If the magnetic field strength is increased above some critical limit the magnetic interaction becomes dominant and the flocculation escalates. The flocculation process proceeds at a high rate and the risk of capturing non-magnetic material is increased.
3. Increasing the magnetic field strength even further has little effect since most of the material is already flocculated, and the remaining material have low magnetization and/or long distance to the nearest neighbouring particle.
Magnetic flocculation often has pronounced effects on the characteristics of pulps and on the degree of packing. It usually increases the apparent viscosity of the suspension, increases the settling rate of the magnetic flocs, and increases the porosity of the settled material (Laurila, 1985).

1.8. Solids concentration of flocculated suspensions

In non-spherical particles the magnetic forces are concentrated to the corners and edges of the particles, this means that particles adhere to each other mainly at these points, and therefore the flocs acquire a porous structure (Lantto, 1977b). Also the maximum solids concentration achievable by sedimentation or filtration is affected by the ambient magnetic field. Eichholz et al. (2012) made DEM simulations of filtration. During their simulations, the filter cake solids concentration was found to vary between 67 vol% solid (for non-magnetic particles) and 38 vol% solids (for particles in a magnetic field intensity of 70 mT). The magnetic ordering of particles led to a lower solids concentration in the sediments, see Figure 11.

Figure 11. DEM-simulation of filter cakes at four magnetic flux densities, the model includes 700 particles (5 µm), after Eichholz et al. (2012).

1.9. Entrainment of non-magnetic particles

Garcia-Martinez et al. (2011) defined three mechanisms, see Figure 12, by which gangue particles can get entrained into magnetite flocs in an external magnetic field:

a) Magnetic flocculation of mixed gangue-magnetite particles with liberated magnetite particles
b) Liberated gangue particles being a link in a chain of magnetite particles.
c) Magnetite chains wrapping around gangue particles.
Their experiments were performed using sedimented particles on a flat surface, but the types of entrainment will be similar for the three-dimensional case. However, case c) will be less likely since more chains of magnetic particles are needed to wrap around a gangue particle in suspension.

Figure 12. Three types of magnetic entrainment of non-magnetic particles. a) Liberated magnetic particles attract mixed particles. b) Non-magnetic particle trapped between several magnetic particles. c) Non-magnetic particles wrapped in by chains of magnetic particles. After García-Martínez et al. (2011).

2 Wet LIMS for magnetite concentration

In the current work the focus is on counter-current type magnetic separators used for cleaning of magnetite ore, when prepared for pelletizing. This means e.g. that the feed material is fine. While this limitation simplifies the description of the process, there are still a large number of factors influencing the magnetic separator performance. Dardis (1989) and Morgan and Bronkala (1993) describe a number of factors affecting process performance, e.g.; the feed rate of magnetic material, magnetic grade of the feed, feed solids concentration, magnet assembly angle, and the drum rotational speed. In addition there are a number of machine design factors which affect the performance, e.g. the drum-to-tank clearance, the separator magnet assembly design, and the separator tank design.

Lantto (1977a, b) studied the factors affecting separation performance and found magnetic flocculation 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 (1977a) 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, 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 (Hopstock, 1985). Rayner and Napier-Munn (2003) investigated the mechanisms controlling the solids concentration of the magnetic
separator concentrate. They proposed that it is a drainage process controlling the solids concentration of the concentrate.

When the feed becomes fine and pure enough the LIMS process shows similarities with a dewatering process. Almost all fine magnetic material is flocculated and brought to the concentrate. Most of the water exit through the tailings stream. The very fine gangue particles tend to act as part of the fluid medium. The misplacement of gangue to the concentrate becomes equal to the fraction of water reporting to concentrate (Hopstock, 1985).

2.1. Separation theory

Separation is the result of several competing forces acting on the feed material. The relative influence of the forces depends on various particle properties. In magnetic separation the most influential forces are; the magnetic force, the hydrodynamic drag force, the force of gravity, the inertial force, and surface and inter-particle forces (Oberteuffer, 1974; Svoboda and Fujita, 2003).

Considering a simple system consisting of one magnetized particle in a magnetic field, and studying Eq. (4) and (7), it can be seen that the magnetic force on a particle is proportional to the particle volume, particle magnetization, and the gradient of the magnetic field. The particle magnetization depends on the particle composition and the ambient magnetic flux density. However, due to magnetic saturation, magnetic flux density is only important up to a certain magnitude, and after saturation the magnetic force can only be increased by increasing the magnetic field gradient, Sundberg (1998).

In laminar flow, the hydrodynamic drag force is proportional to the particle diameter, the velocity of the particle (relative to the surrounding fluid), and the dynamic viscosity of the suspending fluid (according to Stokes’ law, see e.g. Oberteuffer, 1974). The viscosity of the suspending fluid is in turn affected by the suspension solids concentration and the particle size distribution. Also e.g. type of flow and particle shape will affect the hydrodynamic drag force. The force of gravity (buoyancy) is proportional to the particle volume, and to the difference in density between the particle and the suspending medium.

However, when studying single particle systems certain detrimental effects cannot be considered; interparticle hydrodynamic and friction forces together with magnetic flocculation effects have a major influence on the separation process. The magnetic flocculation will increase the influence of the magnetic force on the individual particles, due to increased gradients caused by the flocs. Magnetic flocculation will also decrease the hydrodynamic drag on the individual particles, since the flow is diverted by the flocs. Together the flocculation effects will make magnetic forces on small particles much more influential than if the flocculation effect did not exist.

Due to the combined effects of flocculation and turbulence, single particle models based on first principles should not be used to predict e.g. the recovery of a material in wet LIMS. A major issue is determining the distance a particle needs to travel to finally end
Wet low-intensity magnetic separation: Measurement methods and modelling

up in the concentrate. Based on the separator geometry a reasonable assumption would be in the range of 50 to 100 mm. But in reality, this distance can be much shorter for the majority of the feed particles, due to magnetic flocs extending out from the drum.

### 2.2. Separator tank designs

A number of separator tank designs are available, Figure 13 shows the three main tank designs (adapted mainly from Metso, 2014). The tank and the magnet assembly has been divided into zones using the concepts of Davis and Lyman (1983), and the shaded areas indicate approximate pulp level as in Forciea et al. (1958). The actual pulp level depends on e.g. the feed rate, magnet assembly angle, and the suspension viscosity. Table 2 contains a summary of general properties of the three main types of wet LIMS.

Table 2. General properties of the three main types of wet LIMS (Metso, 2004).

<table>
<thead>
<tr>
<th>Type</th>
<th>Concurrent (CC)</th>
<th>Counter-current (CTC)</th>
<th>Counter-rotation (CR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main use</td>
<td>Cobber</td>
<td>Rougher or finisher</td>
<td>Rougher or finisher</td>
</tr>
<tr>
<td>Particle size</td>
<td>Up to 8 mm</td>
<td>Up to 0.8 mm</td>
<td>Up to 3 mm</td>
</tr>
<tr>
<td>Main advantage</td>
<td>Handle low feed grade and high feed rate</td>
<td>God recovery and grade</td>
<td>High recovery</td>
</tr>
<tr>
<td>Feed grade</td>
<td>Low</td>
<td>High</td>
<td>Any</td>
</tr>
<tr>
<td>Self-levelling</td>
<td>Optional</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Figure 13. Schematic drawings of three wet LIMS tank designs. a) Con-current type. b) Counter-current type. c) Counter-rotation type.

The various separator types available differ mainly in tank and magnetic assembly design. The type of separator most suited for a particular process is determined by the application, factors to consider are:

- Maximum feed particle size
- Feed grade
- Demands on recovery and grade
- Feed throughput.
Separators of the concurrent type are capable of handling large particles, since they are
designed without zones where the material can sediment, and are commonly used as
primary separators. Feed materials with a particle size up to 8 mm (or up to 20 mm
with special arrangements) can be processed. The counter-current type separator is
mainly used to treat very fine particles when high grade and recovery is desired, and
cannot handle large particles, since they will sediment in the feed channel (Metso, 2004;
Sealy and Howell 1977).

2.3. Separator zones

To describe the operation of the wet LIMS, the tank has been divided into a number of
zones, see Figure 13. The pick-up zone is here defined as the part of the tank where the
feed is introduced. The scavenger zone is defined as the shallow part of the tank where
the suspension is transported close to the drum, flowing against the drum rotation. The
dewatering zone is defined as the part of the tank where the concentrate moves towards
the discharge and water is drained by gravity.

2.3.1. Feed section

The purpose of the feed section is to present an even feed to the drum. Before or during
the introduction of the feed to the separator it is usually diluted. The use of water
recirculated from the process has proved to be very suitable for feed dilution. Only in the
last stage of separation there is a reason to use fresh water, and then only for the final
separators (Lantto, 1977a). In counter-current separators the feed rate is kept high to
avoid sedimentation of coarse magnetite particles in the bottom of the tank.

2.3.2. Pick-up zone

In the pick-up zone the feed material reaches the drum. In the pick-up zone, the
position in the feed flow, together with the force balance described above, will
determine whether a particle attaches to a magnetic floc. Lantto (1977b) describes the
behaviour of ferromagnetic particles in the field of a magnetic separator as a three-step
process:

1. Particles in a relatively weak magnetic field become magnetized and align with
the ambient magnetic field
2. The ambient field grows stronger, making the individual grains act as secondary
magnets and the particles begin to gather into groups and floculation occurs
3. When the magnetic force acting on the flocs exceeds the sum of the forces
opposing it, the flocs start to move, and attaches to the surface of the drum.

Also Rayner and Napier-Munn (2000) found that the dominant capture mechanism in
the pick-up zone, particularly at high feed solids content, is through the formation of
elongate flocs. These flocs can have sufficient size and length to either form in contact
with the drum or to migrate towards it at a high rate. Figure 14 shows a numerical
simulation of the material capture process.
2.3.3. Cleaning and dewatering zone

In the first part of the cleaning and dewatering zone flocs of magnetic material (with entrained gangue particles) move along the drum surface towards the concentrate discharge. The material will experience a magnetic field of rotating direction. The field motion agitates the flocs and contributes to the cleaning of the concentrate (Murariu, 2013).

The liquid content in the concentrate is controlled in the upper part of this zone. The suspension level in the dewatering zone should be kept below the concentrate discharge, to allow water to drain away from the concentrate. The solids concentration of the concentrate is normally between 65 wt% and 75 wt% solids. The drainage process also contributes to the cleaning of the concentrate; when the concentrate is dewatered gangue particles are flushed away. Also the amount of very fine gangue in the concentrate is linked to its solids concentration. In the end of the dewatering zone the magnetic field strength decline sharply to allow removal of the concentrate (Lantto, 1977a; Davis and Lyman, 1983; Hopstock, 1985; Rayner and Napier-Munn, 2003a).

2.3.4. Transport and cleaning zone

The transport zone is only present in con-current type separators and has a similar purpose as the dewatering and cleaning zone described above, except for the dewatering function. By using weaker magnets the magnetic field strength and field gradient can be lower in the transportation zone, where the recovered magnetic material is cleaned as it is agitated by the alternating magnetic poles (Davis and Lyman, 1983).

2.3.5. Scavenger zone

In the scavenger zone, pulp of low solids concentration is forced close to the drum, flowing against the drum rotation. The purpose is to recover magnetic material not
directly brought to the concentrate in the pick-up zone, thus increasing recovery of magnetic material. This zone is present in counter-current and counter-rotation type separators. The depth of the scavenger zone is an important factor controlling separator capacity. The minimum distance between the drum and the bottom of the tank in the scavenger zone is usually around 25 mm. Increasing the depth reduces the magnetic force in the bottom of the zone, but on the other hand, the suspension flow rate is reduced (Lantto, 1977a).

2.4. Magnet assembly design

The magnet assemblies have radial or axial pole configurations. The axial configurations are used when the grade of the magnetic concentrate is of importance. The tumbling motion of the particles over the rows of the magnets with alternating polarity facilitates the release of entrained non-magnetic particles and thus improves the grade of the magnetic concentrate. The axial magnet assemblies (Figure 15) normally consist of five to twelve magnetic blocks of alternating polarity, and cover an angle ranging from 90° to 120°. The main poles are made from ferrite (BaFe) or neodymium (NdFeB) permanent magnets. Adjacent magnets are separated by air, steel, or by additional perpendicularly orientated permanent magnets (Svoboda and Fujita, 2003; Murariu and Svoboda, 2003; Svoboda, 2004).

Figure 15. Example of an axial magnet assembly to a full size separator, featuring seven magnetic poles and five intermediate poles.

Specification of magnetic assembly field strength is commonly based on the mean field strength measured between the centre of each gap and the centre of each pole, at a distance of 50 mm from the drum surface. Magnetic flux densities between 50 mT and 120 mT are available, Morgan and Bronkala (1993). This single value is probably oversimplified, as the magnetic field gradient and the pole pitch is also of great importance to separation result, Sundberg (1998). Also the position of the poles relative to the separator zones has a major influence on the separator performance, Dardis (1989).

2.5. Premagnetization

Magnetizing coils are used prior to magnetic separation where premagnetization can create magnetic flocs and reduce the loss of fine (> 10 µm) ferromagnetic particles.
Even in low concentration suspensions magnetic flocculation in a field of 60 mT, and a residence time of less than 0.1 s, can be effective (Benson et al., 1968; Laurila, 1985). The effect of premagnetization is stronger for feed materials containing smaller amounts of magnetite, since the average distance between each magnetite grain is longer. Premagnetization is also more effective if the feed rate is high; if the feed rate is low the material has sufficient time to flocculate inside the separator (Lantto, 1977b).

2.6. Demagnetization

Ferromagnetic materials exposed to the magnetic field of a magnetic separator become magnetized. Demagnetization is applied to achieve deflocculation and better dispersion of the magnetic particles in suspension. Demagnetization can be used between stages of magnetic separation to release non-magnetic particles that are trapped in flocs, thus improving separation result. Without demagnetization, flocs can endure substantially unchanged throughout complicated concentration processes (Laurila, 1985; Lantto, 1977a; Hopstock, 2000).

For demagnetization a time-varying magnetizing field of gradually decreasing amplitude is be used. During demagnetization the particle magnetization go through a series of hysteresis loops with decreasing amplitude, and ultimately converge towards zero net magnetization. For this to be effective the magnetic field must be strong enough to overcome the material coercivity, and have a high enough frequency to avoid particle rotation in the field. In practise the initial magnetic field strength should be approximately five times the material coercivity and the decrease should be about 10% per cycle (Svoboda, 2004).

As for magnetization, the result of demagnetization depends on the material treated. Demagnetization is most efficient when the magnetic material has low coercivity, the alternating magnetic field has high frequency, the fluid has high viscosity, and the particles are irregularly shaped (Laurila, 1985). Hopstock (2000) showed that the coercivity and remanent magnetization increase markedly as the particle size decreases below 10 µm.

3 Ultrasound and flow measurement methods

An ultrasound based flow measurement system measures properties of a fluid or particles in suspension using information carried in ultrasonic pressure waves. The pulse is emitted using an ultrasound transducer excited with a short electric pulse. The ultrasound pulse propagates through the flow and is then detected by the same (or another) transducer.

Lynnworth and Liu (2006) made a review covering the development of ultrasound based flow meters during the second half of the 20th century. According to them the most compelling reasons to select ultrasound based flow measurement methods are their high accuracy (relative uncertainty below 0.5% in good conditions), fast response time (less than 1 ms), and low price. Also, in many cases installation can be convenient through the use of clamp-on sensors. These methods are especially well suited for situations where
optical methods cannot be used due to opaque suspensions, and where nuclear magnetic resonance (NMR) based methods cannot be used due to the presence of ferromagnetic materials.

Ultrasound based methods can be used to measure e.g.; the velocity of a fluid, velocity of particles in suspension, speed of sound in a fluid or suspension, and the sound attenuation. From the measured sound attenuation other properties may also be determined, e.g.:

- Phase concentrations in two-phase suspensions
- Gas average molecular weight
- Temperature and density of pure liquids
- Void fraction in aerated liquid
- Liquid viscosity.

3.1. Ultrasound

Ultrasound is an oscillating pressure wave with a frequency higher than the upper limit of the human hearing range. Measurement devices operate with frequencies from 20 kHz up to several gigahertz. The speed of sound is affected by fluid temperature; in pure water it is e.g. 1482 m/s at 20 °C, and 1509 m/s at 30 °C. The speed of sound is also affected by particles in suspension. As an example, Wiklund and Stading (2008) measured the speed of sound in a mineral slurry with 20 wt% solids at 20 °C to 1530 m/s. The relative difference when compared to pure water is only 3%; in suspensions of low solids concentration this effect is negligible.

3.2. Transducers

An ultrasonic transducer converts electrical energy to mechanical energy, in the form of sound, and vice versa. The main component in a transducer is the piezoelectric element, which can be excited with a high voltage (several hundred volts) during a short period of time (a few microseconds). Figure 16 and e.g. Olympus NDT (2011) describes how the ultrasound pulse propagates from the transducer into a homogeneous liquid, including the near field distance and the divergence angle. Estimating the near field distance can be done as:

\[
N = \frac{d^2}{4\lambda} \left(1 - \left(\frac{\lambda}{d}\right)^2\right),
\]

where \( d \) is the transducer element diameter, and \( \lambda \) is the ultrasound wave length. Sound pulses propagating through fluids will diverge; this is specified using the divergence angle \( \alpha \). At this angle the signal is at half intensity (−6 dB) compared to at the beam axis, and it can be approximated using:

\[
\sin \left(\frac{\alpha}{2}\right) = 0.814 \frac{\lambda}{d}
\]
3.3. Ultrasound scattering

When a sound wave travels through a suspension and interacts with a solid particle, the wave will lose energy, and most of the energy will be lost through scattering. The distance travelled in pure water has very low loss compared to the particle interactions. If the solids concentration of the suspension is low, it can be assumed that any part of a transmitted pulse only interacts with one particle, this is called single scattering. For suspensions of high particle concentration (solids concentration), the scattering theory becomes complicated (Allegra and Hawley, 1972; Challis et al. 2005). Theory regarding single scattering is relatively simple, but can still provide some insight into scattering and attenuation of ultrasound.

Here a simple scattering model for multiphase flows (Carlson and Martinsson, 2002) is used to describe the interaction between an ultrasound wave and a spherical particle (single scattering). The signal energy $\Pi$, relative to the transmitted energy $\Pi_0$, is approximated based on the theory of Urick (1948), as;

$$\frac{\Pi}{\Pi_0} = e^{-\alpha x},$$  \hspace{1cm} (10)

where $x$ is the axial distance from the transducer, and $\alpha$ is the coefficient of excess attenuation;

$$\alpha = c_s A \frac{x}{\lambda^4 \rho_l} r^3$$ \hspace{1cm} (11)

and where $c_s$ is the solids concentration, $A$ is a constant, $r$ is the particle radius, $\lambda$ is the ultrasound wave length, $\rho_l$ is the liquid density, and $\rho_s$ is the solids density. As seen from Eq. (11) the signal attenuation has:

- Quartic dependency on the ultrasound frequency ($f = 1/\lambda$); high frequencies are attenuated faster
- Cubic dependency of the particle radius; small particles create less attenuation
- Linear dependency on the solids concentration; signal is attenuated faster in suspensions of high solids concentration.
As the solids concentration increases or the number of particles increases (particle size decreases), the distance between each particle is reduced. In a suspension with high enough solids concentration the single scattering assumption will no longer hold. In some cases, e.g. when long measurement distance (≥ 1 m) and high transmitter frequency (5 MHz) is needed; this limit can be as low as 0.1 vol% solids, Hunter et al. (2012b).

According to continuum scattering theory particles separated by less than one half wavelengths ($\lambda/2$) cannot be resolved by a transducer (Angelsen, 1980). However, scattering of ultrasound pulses can also arise from local fluctuations in the compressibility and the mass density of the suspension, Hauptmann et al. (2002). Table 3 contains four commonly used ultrasound transmitting frequencies together with their wavelength (for a speed of sound of 1500 m/s) and particle separation limit. In Figure 17 concentration gradients in turbulent flow is illustrated.

Table 3. Typical transducer frequencies and corresponding wavelengths and minimum particle separation limits. Data calculated for a speed of sound in water at 20 °C.

<table>
<thead>
<tr>
<th>Manufacturer specified centre frequency (f₀)</th>
<th>Wavelength (λ)</th>
<th>Particle separation limit (λ/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 MHz</td>
<td>1.50 mm</td>
<td>0.75 mm</td>
</tr>
<tr>
<td>2.25 MHz</td>
<td>0.67 mm</td>
<td>0.33 mm</td>
</tr>
<tr>
<td>3.5 MHz</td>
<td>0.43 mm</td>
<td>0.22 mm</td>
</tr>
<tr>
<td>5.0 MHz</td>
<td>0.30 mm</td>
<td>0.15 mm</td>
</tr>
</tbody>
</table>

Figure 17. Image of 2 µm glass beads in homogeneous isotropic turbulence, after Wood et al. (2005).

3.4. Backscattered signal strength and signal attenuation

To get a sufficiently strong echo from the whole depth of interest, there has to be a balance between backscatter strength and signal attenuation. Strong interaction gives
high signal attenuation and low penetration depth. Weak interaction on the other hand, gives a weak signal (bad contrast) and low measurement accuracy. Important factors for backscatter strength and signal attenuation are the ultrasound frequency, suspension solids concentration, and the particle size distribution.

Figure 18 shows an example of how these factors interrelate. In a) the maximum power spectrum amplitude occurs at the centre frequency (2.25 MHz) and the amplitude increases with concentration over all frequencies. In b) the attenuation increases with concentration as well as frequency. At zero concentration, the acoustic attenuation is close to zero, since the only attenuation occurring in the absence of particles is due to absorption (Furlan et al., 2012).

![Figure 18](image)

**Figure 18.** Example of relation between; a) acoustic backscatter amplitude and b) attenuation, vs. ultrasound centre frequency and suspension solids concentration. The backscattered signal is measured in a suspension of 195 µm particles in a Ø25 mm pipe. After Furlan et al. (2012).

### 3.5. Interaction volume

In ultrasonic measurement devices of pulse-echo type, an ultrasound pulse is transmitted into the flow, and the backscattered echo is sampled. During signal processing it is assumed that the volume of flow responsible for the sampled backscatter intensity in each sample, the interaction volume, is of negligible size. In reality the interaction volume has a small, but not always negligible size. The size and shape of this interaction volume are two factors determining the flow meter sensitivity and accuracy. The velocity measurements obtained can be shown to be a weighted average of the sound intensity and the local flow velocity over the interaction volume (Jorgensen et al., 1973). The dimensions of the interaction volume can be approximated as a flat cylinder with; radius equal to the transducer radius, and the length depending on the electrical pulse length \( t_e \) together with the speed of sound in the suspension. In this cylindrical volume the sound intensity, resulting from the excitation by the electrical pulse in Figure 19a, will be distributed according to Figure 19b.
3.6. Ultrasound based flow measurement methods

Ultrasonic flow measurement methods are (almost) non-invasive quantitative or qualitative methods capable of operating in opaque suspensions. These methods have several advantages over comparable methods when applied in the process industry (Hauptmann et al., 2002):

- Non-invasive measurement
- In-line measurement
- Rapid response, usually a fraction of a second
- Low power consumption
- Excellent long-term stability
- High resolution and accuracy.

Depending on the application there are also issues regarding the use of ultrasonic sensors. First the substances under investigation must be acoustically transparent for measurements to be successful. Liquids are usually acoustically transparent, but mixing them with air or high concentration of solid particles makes a more challenging environment. Also the components of the measurement system (e.g. transducer frequency) often need to be matched to the monitored suspension, either by exact knowledge of the acoustic properties of the substances, or by trial and error. Also ultrasonic signals tend to be complicated and need relatively complex signal processing (Crawford and Hay, 1993; Hauptmann et al., 2002).

3.6.1. Velocity measurements

There are four main categories of ultrasound based flow velocity measurement methods; transit time, Doppler-based, speckle correlation, and passive techniques. Most of these methods originate from the field of medicine or navigation but have in more recent years found other applications, see e.g. Hein and O'Brien (1993) and Hauptmann et al. (2002).
Transit time methods measure the difference in transit time of ultrasonic pulses propagating with, and against, a pipe flow. The time difference is a measure of the average velocity of the fluid along the path of the ultrasonic beam. By using the absolute transit times and the geometry of the setup, both the averaged fluid velocity and the speed of sound can be calculated. In variants of this method the pulse propagates through the flow more than once. Generally, a higher number of passes through the flow gives better accuracy, given that the pulse is not extinct.

In Doppler based flow meters, short ultrasound pulses are transmitted into the suspension flow. The pulses interact with the suspension and create backscatter waves which are detected by the same, or another transducer. The transducer response is sampled and the signal is then analysed for a frequency shift. The frequency shift (Doppler effect) happens when the ultrasonic pulse is reflected by suspended particles or gas bubbles in motion. Doppler based methods measure the velocity of particles in suspension.

The speckle correlation based methods operate in a similar manner as the Doppler based methods. The main difference is that two consecutive pulses are needed, and how the sampled signals are processed. Here the cross-correlation between two consecutive ultrasound echoes is calculated, and a time-delay is estimated. From this time delay the particle displacement and velocity can be calculated. Dotti et al. (1976) used an ultrasonic cross-correlation method to measure blood flow and Carlson and Ing (2003) used a similar method to measure in flow of magnetite suspensions. Variants of this method have been given several names, e.g. ultrasonic velocity profiling (UVP), ultrasonic speckle correlation velocimetry and acoustic backscatter system (ABS). In a review by Hein and O’Brien (1993) the development of cross-correlation based ultrasound velocity measurements is summarised.

With passive methods no signal is generated, instead ultrasonic information is collected by an array of sensors mounted to a pipe. The flow velocity is calculated by tracking vibration patterns from vortices or other disturbances travelling with the flow (O’Keefe et al., 2010).

3.6.2. Solids concentration measurements

In suspensions of low solids concentration, where conditions close to single scattering can be assumed, there are a number of methods available to characterize suspensions, both in the laboratory and in-line. Challis et al. (2005) made a review covering scattering theories and ultrasound based methods for measuring e.g.; the solids concentration and the particle size distribution of colloidal dispersions. Thorne and Hanes (2002) reviewed measurement methods applicable in a marine environment, where the suspension solids concentration commonly is less than 1 g/litre. For suspensions of low solids concentration, the backscattered signal can be converted quantitatively to solids concentration (in known particle systems) by comparing the echo to single scattering theory.
Laboratory measurements have shown a linear dependency of the signal attenuation on the suspension solids concentration up to 30 g/litre (1 vol% solids), indicating that the single scattering assumption is valid up to that concentration (Crawford and Hay, 1993). Carlson and Martinsson (2002) also compared measurements to single scattering theory. In mineral suspension a linear relationship was found between the coefficient of excess attenuation and the suspension solids concentration, for solids concentrations of up to 7 wt% (2.6 vol%) dolomite particles. Hunter et al. (2011) used a pulse-echo system to monitor particle settling rates, sediment bed formation, and bed compaction. These experiments were made in suspensions of 5 wt% (2 vol%) glass beads.

For particle concentrations encountered in many applications in the process industry, single scattering cannot be assumed, and as the suspension solids concentration increases the environment becomes more challenging. In some cases, when the suspension can be assumed to be homogeneous, there are still possibilities to measure changes in solids concentration, by correlating the signal response levels with known standards. Hunter et al. (2012a) estimated solids concentration in homogeneous suspensions with up to 10 wt% (4 vol%) glass beads. Wöckel et al. (2012) used a narrow measurement cell, resembling what can be found in e.g. analytical instruments. In homogeneous suspensions a linear relationship was found between the suspension solids concentration and the signal amplitude standard deviation. The measurement depth was e.g. 16 mm in a suspension of 4.5 vol% solids, and 5 mm in a suspension of 30 vol% solids. Weser et al. (2013a, b) used the same setup as Wöckel et al. (2012) to study how the peak backscatter amplitude increase with the mean particle size. When using a 6 MHz transducer good correlation were found for mean particle sizes between 10-54 µm, and when using 10 and 14 MHz transducers good correlation were found for particle sizes of 7-23 µm.

Additionally, if the suspension can be assumed to be homogeneous, multi-frequency techniques offer the possibility to measure particle sizes simultaneously with concentration. By doing measurements at three transmitting frequencies, both the average particle size, and the solids concentration are calculated from the backscattered acoustic pressure amplitude (Crawford and Hay, 1993). Betteridge et al. (2008) also used a triple frequency ABS, with the transducers operating in transceiver mode at 1.0, 2.0 and 4.0 MHz, to measure particle size and concentration in a marine environment. In laboratory conditions, and further increasing the number of ultrasound frequencies, it is even possible to estimate the particle size distribution from the sound attenuation. Measuring attenuation for 31 frequencies during 60 s can generate a particle size distribution with 31 size classes (Pankewitz and Behrens, 2009). In the flow conditions present in a wet LIMS, however, neither single scattering, nor homogenous suspensions can generally be assumed.
This chapter describes the experimental setups, magnetite materials, ultrasound based measurement methods, and the signal processing methods used during this work. In the last section the experimental conditions used in the five experiments are summarized.

1 Experimental setups

The experiments made during this work are carried out using three experimental setups. The main part of the first setup is a rectangular flow cell. The second setup is built around a bench scale wet LIMS. Both these setups were built and operated in the mineral processing laboratory at LTU. The third setup is built around a pilot scale wet LIMS in the pilot plant at the LKAB R&D facilities in Malmberget, Sweden.

1.1 Rectangular flow cell

The flow cell, see Figure 20, has a depth of 50 mm, width of 75 mm and length of 1 m. The dimensions of the flow cell were selected as a compromise between pump capacity, realistic measurement depth, achievable flow rate, and system volume. The walls are made from 12 mm clear polycarbonate. The ultrasonic transducer is fitted at a 45° inclination angle in one end of the cell. The transducer is mounted at an angle since the flow velocity is measured in the axial direction of the transducer and then projected onto the main flow direction. A less steep inclination angle gives more accurate measurements at the expense of shorter (vertical) penetration depth.

![Figure 20](image-url)
exchanger fed with cold tap water. All parts are connected in closed loop using rubber hosing with an internal diameter of $\varnothing 50$ mm. To evacuate entrained air, or flush away settled particles from the transducer recess, a peristaltic pump (Watson-Marlow 503S, www.watson-marlow.com) is used. The flow rate (through a $\varnothing 1.5$ mm hole) is negligible compared to the main flow.

1.2. Bench scale wet LIMS

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 Figure 21. The characteristic 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 transparent polycarbonate, and a rear frame of stainless steel. Two ultrasound transducers (Olympus V306, 2.25 MHz) were mounted using modular sensors holder in the separator tank, see enlargement in Figure 21.

![Figure 21. Bench scale wet LIMS setup with purpose built CTC-tank. System layout consisting of; LIMS, mixer (M), pump (P), heat exchanger (HE), and sampling point (S). The figure also includes the data acquisition equipment; pulser receiver (PR), digitizer (DAQ) and computer (PC). The close up shows the four available transducer positions.](image)

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. The parts are connected using rubber hosing with an internal diameter of $\varnothing 50$ mm. The flow is driven by a progressing cavity pump (Netzsch NM053BY01L06B) controlled by an AC drive (Emotron VFX48-010). The suspension temperature is stabilised by a heat exchanger fed with cold tap water. To keep the sensors free from settling particles a small water flow is introduced close to the transducers using a peristaltic pump (Watson-Marlow 503S). This small pump is paused during all ultrasound measurements to avoid any potential interference with the flow.
1.3. Pilot scale wet LIMS

The pilot scale experiments were conducted *in-situ*, using a pilot scale wet LIMS, see Figure 22. The separator, a SALA counter-current separator, $\varnothing 916 \times 300$ mm (TA-623780-2), were connected in closed loop with a vertical tank pump (Sala SPV-232) feeding the separator at a rate of $2.4 \text{ dm}^3/\text{s}$ ($8.6 \text{ m}^3/\text{h}$). Both the magnetic and the non-magnetic products from the separation are circulated back to the pump sump. To keep the sensors free from settling particles a small flow is introduced close to the transducers using a peristaltic pump (Watson-Marlow 503S). This pump is stopped momentarily during all ultrasound measurements. Two ultrasound transducers (Olympus V306, 2.25 MHz) were mounted in the bottom of the separator tank, at a relative angle of 60° or 90°, see enlargement in Figure 22.

![Figure 22](image-url)

Figure 22. Pilot scale setup consisting of: LIMS, pump (P), feed sampling point (S1), and concentrate sampling point (S2). Data acquisition equipment is also included; pulser receiver (PR), digitizer (DAQ) and computer (PC). Close up shows four of the eight available transducer positions, the other four are available by interchanging the sensor holders.

2 Materials

Two materials are used, one for the laboratory experiments at LTU, and another (similar) material for the pilot scale experiments in Malmberget, Sweden. The dry magnetite powder is mixed with tap water to reach the desired concentrations. The stated concentrations are measured after giving the system time to reach a steady state, by sampling the feed stream, drying the sample, and back-calculating the solids content.

For the laboratory experiments a magnetite material (approx. 69% Fe) was supplied by the LKAB from the KA1 concentrator in Kiruna, Sweden. It was sampled from the feed stream to the second stage of wet LIMS (overflow hydrocyclone). The magnetite material density is 5.0 kg/dm³, as measured with a pycnometer (Micromeritics 1305, www.micromeritics.com). Particle size analysis, by laser diffraction (Cilas 1064,
www.cilas.com) showed that the median diameter ($d_{50}$) is 29 µm and wet sieving showed that approximately 85 wt% of the material is finer than 45 µm.

The second magnetite material (approx. 70% Fe), used in the pilot scale experiments, was sampled from the pellet concentrate stream in the LKAB concentrator in Malmberget. The material (Sample number MPC KS2010-0371-M) has a density of 5.2 kg/dm³, $d_{50} = 35$ µm, and wet sieving showed that 63 wt% of the material are finer than 45 µm.

3 Ultrasound data acquisition

In this section the ultrasound based measurement method is described, including data acquisition equipment and sampling procedures. The measurements are pulse-echo measurements; one transducer transmits ultrasound pulses into the flow, and then senses the backscattered echo. Measurements are divided in one-dimensional (1D) and two-dimensional (2D) measurements. The 1D measurements are used in the flow cell, where a main direction of flow can be assumed. The 2D measurements are used in the bench and pilot scale wet LIMS, to be able to estimate both flow magnitude and direction of the velocity. To get information about local changes in solids concentration in the suspension, the data acquired for the velocity measurements are reused together with the signal processing steps described in section 4.3.

3.1 Measurements using one transducer

The method used for estimating the particle velocity in the suspension flow is called ultrasonic velocity profiling (UVP). It is an ultrasound based pulse-echo method using windowed cross-correlation to estimate local particle velocity. UVP is used when a main direction of flow can be assumed, and the transducer is mounted in the cell wall at an inclination angle of e.g. 45°, see Figure 23a. The transducer first transmits a short pulse into the flow, and is then used as a receiver to record the backscattered wave (echo). The backscattered wave contains information about the particles in the flow. By acquiring two backscattered signals closely spaced in time and then cross-correlating them it is possible to follow the movement of the particles in suspension.

<table>
<thead>
<tr>
<th>Manuf. part no.</th>
<th>Manufacturer specified centre frequency ($f_c$)</th>
<th>Approximate wavelength ($\lambda$)</th>
<th>Divergence half angle</th>
<th>Near field</th>
</tr>
</thead>
<tbody>
<tr>
<td>V303</td>
<td>1.0 MHz</td>
<td>1.50 mm</td>
<td>3.5°</td>
<td>27 mm</td>
</tr>
<tr>
<td>V306</td>
<td>2.25 MHz</td>
<td>0.67 mm</td>
<td>1.5°</td>
<td>61 mm</td>
</tr>
<tr>
<td>V382</td>
<td>3.5 MHz</td>
<td>0.43 mm</td>
<td>1.0°</td>
<td>94 mm</td>
</tr>
<tr>
<td>V309</td>
<td>5.0 MHz</td>
<td>0.30 mm</td>
<td>0.7°</td>
<td>135 mm</td>
</tr>
</tbody>
</table>
The measurements are made using the immersion transducers listed in Table 4. The transducers are operated by a computer-controlled pulser-receiver (Panametrics 5800PR, www.olympus-ims.com). Pulse timings, see Figure 23b, are controlled by a signal generator (Wavetek Model 19). The received backscatter signal is processed by a digitizer (ADQ214, www.spdevices.com). The whole data acquisition process is controlled by a MATLAB script.

![Figure 23a](image1.png)

**Figure 23a.** Cross section of a flow cell showing transducer (TDX) inclined at an angle $\theta$, ultrasonic pulse path, and the concept of interaction volume with diameter $d$ and length $l$. A typical turbulent flow velocity profile is included to the right. **b)** Schematic description of data acquisition and sampling for the 1D UVP method. Filled circles indicate when the transducer is excited, and high level indicates when the digitizer is sampling the transducer.

### 3.2. Measurements using two transducers

In Paper IV the UVP method is extended to estimate not only particle velocity in the direction of the transducer, but also particle velocity in a two-dimensional plane. This is accomplished by combining the measurements from two simultaneous UVP measurements. 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 Figure 24, both transducers can be sampled in the same time span.

![Figure 24](image2.png)

**Figure 24.** Schematic description of data acquisition and sampling for the 2D UVP method. One transducer is connected to each channel. Filled circles indicate when the transducers are excited, and high level indicates when the digitizer is sampling the transducers.
The measurements are made using two transducers (Olympus V306), both with a centre frequency of 2.25 MHz. This centre frequency was selected to give a balance between signal strength and measurement depth, see e.g. Paper I and II. Each transducer is controlled by one pulser-receiver (Panametrics 5800PR and 5072PR). The received backscatter signal is processed by a digitizer (ADQ214). Pulse timings are controlled by a microcontroller (Arduino Dueilanove, www.arduino.cc) running custom software. Before each ultrasound measurement the suspension temperature is measured using a digital thermometer (ASL F250 MKII). The whole data acquisition process is controlled by a MATLAB script.

4 Signal processing

In this section theory regarding the calculation of the simultaneous velocity and concentration profiles is presented. The theory has been divided into three parts; the estimation of velocity profiles, combination of 1D velocity profiles into 2D velocity patterns, and the estimation of solids concentration variations.

4.1 Ultrasonic velocity profiling

In this method a transducer first transmit a short pulse and is then used as a receiver to record the backscattered wave (echo). This backscattered wave contains information about the particles in the flow. By acquiring two backscattered signals closely spaced in time and then cross-correlating them, it is possible to follow the movement of the particles in suspension. 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.

To acquire one backscatter signal, the ultrasound transducer transmits a short pulse into the flow. The sound backscattered from the particles in suspension is then sampled at a sampling interval \( T_s = 1/f_s \) and stored as the signal

\[
p[n] = p_i(nT_s), n = 0, 1, \ldots, N - 1.
\]  

(12)

Two of these signals \((i = 1, 2)\) are acquired at a pulse-repetition frequency (PRF) so that the time between the two acquisitions is \( T_{\text{PRF}} = 1/\text{PRF} \). If the PRF is high enough, it can be assumed that the particles in the interaction volume has moved like an entity, so that the backscatter signatures differ only by a time delay \((\tau_0)\), proportional to the movement of the suspension during the time \( T_{\text{PRF}} \). This time delay can be found by a simple cross-correlation of the two echoes, as

\[
\tau_0 = \arg \max_{\tau} \mathcal{C}_m
\]  

(13)

i.e. the time delay between the echoes is found at the lag \((\tau)\) between the echoes that maximizes the cross-correlation between them.

Since the particle velocity varies throughout the flow the displacement of the flow has to be considered a function of depth. Therefore the cross-correlation between short
segments of $p_1[n]$ and $p_2[n]$ are computed, thus resulting in one time delay estimate for each such pair of segments. In other words, let

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

be two $M$ sample long windows from the sampled signals $p_1[n]$ and $p_2[n]$, respectively, where $k = 0, 1, \ldots, N - M - 1$ is the window position. For each value of $k$, the time delay is then found as the lag maximizing the cross-correlation function between $x_1$ and $x_2$, as in Eq. (13).

Since the time between the two backscatter signals is known it is possible to calculate the particle velocity once these delays have been determined. The particle velocity is computed as

$$
\mathbf{v} = \frac{n_0 T_s}{2 \Delta f},
$$

where $n_0$ is the time delay, $T_s$ is the sampling time, and $\epsilon$ is the speed of sound in the fluid. To obtain a better estimate of the particle velocity profile, the above procedure is repeated $Q$ times. The profiles are then combined by computing the arithmetic mean of all estimated velocity profiles, as;

$$
\mathbf{v}_0 = \frac{1}{Q} \sum_{q=1}^{Q} \mathbf{v}_q.
$$

For the 1D measurements in the flow cell the velocity is projected onto the bulk flow direction, using the inclination angle of the transducer (45°). In Paper I methods for robust signal processing of weak signals are investigated.

### 4.2. Ultrasonic velocity profiling in two dimensions

To be able to acquire the particle velocity in two dimensions, two transducers are needed to create two velocity vectors. The combined velocity is calculated using three planes per data point in $\nu$, see Figure 25. One plane is defined by each of the two velocity measurements, and a third plane is defined by assuming that the flow velocity perpendicular to both transducers is zero.

The scalar particle velocity ($\nu$) in the direction of each transducer ($t = 1, 2$) is calculated using UVP, as above. Let $\hat{n}_t$ be a unit vector in the axial direction of each of the transducers, then a velocity vector, in the axial direction of the transducer, is calculated as $V_t = \nu \hat{n}_t$. Using $V_t$ as points and $\hat{n}_t$ as normal vectors two planes are defined in velocity space, and the third plane is defined as

$$
R_3 = \hat{R}_3 \times \hat{R}_3, \quad v_3 = 0.
$$

39
Finally the combined velocity vector is calculated as the point of intersection between these three planes;

\[ \mathbf{v}_c = \frac{(\mathbf{v}_1 \cdot \mathbf{n}_3)(\mathbf{n}_2 \times \mathbf{n}_3) + (\mathbf{v}_2 \cdot \mathbf{n}_3)(\mathbf{n}_1 \times \mathbf{n}_3) + (\mathbf{v}_3 \cdot \mathbf{n}_3)(\mathbf{n}_1 \times \mathbf{n}_2)}{\mathbf{n}_1 \cdot \mathbf{n}_2 \cdot \mathbf{n}_3}. \]  

(18)

The measurement position \( (P_t) \) are calculated using the known centre positions of the transducer faces \( (q) \), the sample acquisition time \( (nT) \), and speed of sound in water \( (c_w) \) at the measured temperature;

\[ P_t = q_t + \frac{nT \cdot c_w \cdot a_m}{2}. \]  

(19)

For the presentation of the results, the measurement position \( (P) \) is put in the middle between the two original measurement positions.

\[ P = \frac{P_1 + P_2}{2}. \]  

(20)

The two measurements are aligned using the point where they intersect; see the close up in e.g. Figure 22. Equation (18) could also be used to calculate the velocity in 3D-space if a third measurement was made.

![Figure 25. Description of the method used to calculate on velocity vector, see e.g. Figure 36c. Velocity components are defined positive when particles are moving towards the transducer.](image)

### 4.3. Power spectral density indicating solids concentration

By analysing the power spectral density (PSD) of the same sampled signal, as used for the UVP measurements above, qualitative information about variations in the suspension local solids concentration can be extracted. The statistics of the signal vary with solids concentration, particle size distribution, particle density, etc. In the present work it is reasonable to assume that most of the variations in these factors originate from variations in local solids concentration. In that case, based on short-time spectral analysis of the backscattered sound, variations in local solids concentration can be visualized.

The signal, \( p[n] \) in Eq. (12), is random by nature, and due to attenuation and multiple scattering (in high concentration suspensions), the underlying random process cannot be assumed to be stationary. This means that the signal characteristics will vary as a function
of depth, local solids concentration, etc. For a short segment of $p[n]$, however, it may be assumed stationarity, at least in a wide sense. These short segments are defined as in Eq. (14) above, and $m = 0, 1, \ldots, M - 1$ is the sample position in the window. The autocorrelation sequence of $x[n]$ is then defined as

$$r_{xx}[l] = E\{x_k[m + l] x_k[m]\},$$

where $*$ denotes the complex conjugate and $l$ is the lag. Assuming $x_k[n]$ is real-valued and stationary, this can be estimated from the measurements as

$$\hat{r}_{xx}[l] = \frac{1}{M} \sum_{m=0}^{M-1} x_k[m + l] x_k[m].$$

Thus, the autocorrelation sequence is a measure of how similar the signal is to a delayed version of itself (Hayes, 1994).

The PSD of $x_k[n]$ can be estimated as the periodogram of $x_k[n]$, which is the Fourier transform of $r_x[l]$, given by

$$S_x(\omega) = \sum_{l=-M+1}^{M-1} \hat{r}_{xx}[l] \omega[n] e^{-j\omega l},$$

where $\omega = 2\pi f$ is the angular frequency, and $\omega[n]$ is a windowing function, here chosen to be an $M$ sample Hanning window, see Hayes (1994). Since attenuation and backscatter intensity can be assumed to depend on the concentration of particles in the suspension, studying $S_x(\omega)$ as a function of depth should give an indication of changes in the local solids concentration. Hence, for each window position $k$, the PSD is estimated as above. To obtain better estimates of the particle velocity profiles, the above procedure is repeated $Q$ times, each resulting in an estimated PSD. These are then combined by computing the arithmetic mean, as

$$S_x = \frac{1}{Q} \sum_{k=1}^{Q} S_k.$$

5 Experiments

In this section five experiments are summarized. The first three experiments are carried out in the rectangular flow cell. In the first experiment the local flow velocity is measured in undisturbed turbulent flow. The second experiment is similar to the first, but this time the pump is stopped, and the particles are allowed to settle. In the third experiment an assembly of permanent magnets is used to create a build-up of magnetic material in the measurement zone. During the settling and magnetic capture processes, both the local flow velocity and the variations in solids concentration are monitored. The fourth and fifth experiments are both carried out in realistic geometries; in a bench and a pilot scale wet LIMS, respectively. Particle velocity is measured in two dimensions, and the build-up on the separator drum is monitored. Properties of the measurement system and the signal processing algorithm are presented in Table 5.
Table 5. Properties of the measurement system and signal processing algorithm. Column 1a and 1b is used in undisturbed flow in the flow cell, 2 is used in settling suspension, 3 is used during magnetic capture, 4 is used in the bench scale LIMS, and 5 is used in the pilot scale LIMS.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>1a</th>
<th>1b</th>
<th>2 &amp; 3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transducer c. frequency ( (f_c) ) [MHz]</td>
<td>1, 2.25</td>
<td>1, 2.25, 3.5, 5</td>
<td>2.25, 3.5</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>Sampling frequency ( (f_s) ) [MHz]</td>
<td>400</td>
<td>200</td>
<td>100</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Sample bit depth [bit]</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Sample length ( (N) ) [samples]</td>
<td>51200</td>
<td>24000</td>
<td>12000</td>
<td>32000</td>
<td>32000</td>
</tr>
<tr>
<td>Sampling duration [µs]</td>
<td>128</td>
<td>120</td>
<td>120</td>
<td>80</td>
<td>160</td>
</tr>
<tr>
<td>Sampling depth * [mm]</td>
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<td>90</td>
<td>90</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>PRF ( (1/T_{PRF}) ) [kHz]</td>
<td>5</td>
<td>8</td>
<td>8</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Measurements ( (Q) ) [signal pairs]</td>
<td>200</td>
<td>200</td>
<td>2048</td>
<td>512</td>
<td>512</td>
</tr>
<tr>
<td>Measurement rate [Hz]</td>
<td>n/a</td>
<td>n/a</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Measurement duration [s]</td>
<td>n/a</td>
<td>n/a</td>
<td>10.24</td>
<td>2.56</td>
<td>2.56</td>
</tr>
<tr>
<td>Window length, UVP ( (M) ) [samples]</td>
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<td>1000</td>
<td>800</td>
<td>3100</td>
<td>1600</td>
</tr>
<tr>
<td>Window length, PSD [samples]</td>
<td>n/a</td>
<td>n/a</td>
<td>800</td>
<td>3100</td>
<td>1000</td>
</tr>
</tbody>
</table>

* In the axial direction of the transducer.

5.1. Experiments with undisturbed flow in the flow cell

In these experiments magnetite suspensions are pumped through the rectangular flow cell, see Figure 23a, at a constant bulk flow rate. The flow velocity is measured repeatedly in undisturbed turbulent flow, using UVP as described above. To ensure sufficient mixing of the suspension (by turbulence) the bulk flow speed is kept at 1 m/s for at least 60 s before each measurement. The small peristaltic pump was used to extract entrained air from the recess by the transducer. Measurement system properties are listed in Table 5, column 1a and 1b.

To assess the potential of the method in conditions related to wet LIMS transducers with four centre frequencies; 1, 2.25, 3.5 and 5 MHz were evaluated in varying flow conditions. The mean flow velocity was varied between 0.5 and 1 m/s. Below 0.5 m/s the flow conditions could not be assumed homogeneous due to particle settling, and 1 m/s was the maximum achievable bulk flow speed with the setup. Feed suspensions with solids concentrations up to 9 vol% solids were used, being representative for the conditions in the wet LIMS.

5.2. Experiments with settling suspension in the flow cell

In the experiments with settling suspension the ultrasound measurement system is used to monitor the process of suspension settling, see Figure 26. Magnetite suspensions are pumped through the rectangular flow cell, as above, and when steady state is reached (after 60 s) the pump is stopped and the suspension is allowed to settle. The data
acquisition process is initiated as the pump starts to decelerate. The small peristaltic pump was used to extract entrained air from the recess by the transducer. Measurement system properties are listed in Table 5, column 2.

The purpose of these experiments is to study if the local solids concentration in a settling suspension can be monitored using pulse-echo ultrasound. The controlled environment and isolated physical phenomena makes it easy to predict the expected result. The settling creates a region with a strong concentration gradient; a settling interface (also referred to as a mud line). If the particle concentration is low the settling proceeds at a constant velocity, but as the solids concentration below the settling interface becomes high enough the style of settling changes from free to hindered settling, reducing the settling velocity.

By varying the suspension solids concentration a number of cases are studied, see Table 6. However, to achieve sufficient signal quality the transducer centre frequency was changed with suspension solids concentration. For the low levels of suspended particles the 3.5 MHz transducer was used, and for the higher levels of solids concentration the 2.25 MHz was used.

Table 6. Solids concentration levels used in the flow cell.

<table>
<thead>
<tr>
<th>Level</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solids concentration [vol%]</td>
<td>0.23</td>
<td>0.78</td>
<td>1.4</td>
<td>2.8</td>
<td>3.7</td>
<td>6.9</td>
<td>7.5</td>
</tr>
<tr>
<td>Solids concentration [wt%]</td>
<td>1.2</td>
<td>3.8</td>
<td>6.7</td>
<td>13</td>
<td>16</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>TDX frequency (f) [MHz]</td>
<td>3.5</td>
<td>3.5</td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Figure 26. Suspension settling, dark colour indicates high particle concentration. Before time 0 there is a turbulent flow through the flow cell. As the pump is decelerated to a stop, the suspension starts to settle, and sediment begins to form on the bottom of the cell.

5.3. Experiments with magnetic particle capture in the flow cell

In this experiment the possibilities to use ultrasound to monitor the build-up of magnetic material in a magnetic field is investigated in controlled conditions. Magnetite suspensions of varying solids concentration are pumped through the flow cell, and an assembly of neodymium magnets (grade N35) is introduced to attract and capture the ferromagnetic magnetite particles. Three magnets of dimensions 45x25x10 mm were
used together with two 6 mm plastic spacers, see Figure 27. The ultrasound based measurements were used to monitor the build-up process, and to measure the ultimate thickness of the magnetic build-up when the capturing process had reached its steady state (after 60 s). The small peristaltic pump was used to flush the transducer with water prior to each measurement, to remove sediment particles. Measurement system properties are listed in Table 5, column 3.

Conditions resembling those inside a wet LIMS are studied by varying the suspension solids concentrations, suspension flow rate, and the magnetic field strength in the flow cell. The suspension solids concentrations was varied between 0.2 and 7.5 vol% solids, and the flow velocity was varied between 0.5 m/s and 1.0 m/s. The magnetic field strength was varied between 46 mT and 166 mT by placing 10 mm plastic spacers between the magnet assembly and the flow cell. The field strength was measured in an empty flow cell, using an F.W. Bell 610 magnetometer, at a distance \(d_{mf}\), see Figure 27. Ultrasound measurements were made for all combinations of the factor levels in Table 6 and Table 7, resulting in 72 runs. Additionally, for each level of solids concentration, one combination was run three times to be able to assess the repeatability in the experiment.

![Figure 27. Setup used when studying capture, and build-up, of magnetic particles by a set of permanent magnets. \(M\) indicates direction of magnetization and the red arrow indicates where the magnetic field strength was measured.](image)

<table>
<thead>
<tr>
<th>Level</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean flow velocity</td>
<td>0.5 m/s</td>
<td>0.75 m/s</td>
<td>1.0 m/s</td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>45.5 mT</td>
<td>83.5 mT</td>
<td>166 mT</td>
</tr>
<tr>
<td>(distance, (d_{mf}))</td>
<td>(32 mm)</td>
<td>(22 mm)</td>
<td>(12 mm)</td>
</tr>
</tbody>
</table>

Table 7. Factor levels of the experiment used to study particle capture by permanent magnet in the flow cell. Additionally the same levels of solids concentrations as presented in Table 6 were used.
5.4. **Experiments in the bench scale wet LIMS**

The purpose of the experiments in the bench scale wet LIMS was to develop a method for 2D measurements in realistic separator geometry. The process is simplified considerably by using well-defined and easy to access laboratory conditions, see Figure 21. The separator is run in realistic operational conditions, and the conditions are varied according to a designed experiment. The flow in the concentrate dewatering zone is measured repeatedly, using the methods described above to estimate 2D velocity profiles and get information about variations in solids concentration. The measurements are made after the separation process has reached a steady state (after 120 s). Measurement system properties are listed in Table 5, column 4. During each experiment in the bench scale wet LIMS a 10 s video of the material transport was captured using an industrial camera. The camera used was an 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.

5.4.1. **Design of experiment**

The investigation is carried out as a designed experiment, a 2-level factorial design of four factors. The factors included are the feed solids concentration, feed rate, drum rotational speed, and the magnetic assembly angle, see Table 8. With this experimental setup it was not feasible to vary the feed solids concentration independently. Neither was it possible to get a reliable magnet assembly angle in-between the low and the high angles. To still get some indication of the repeatability it was assessed separately for each of the two concentration levels; two centre points were selected and run three times each. For the centre points a mean drum rotational speed of 55 rpm, a slurry feed rate of 30 dm³/min, and a magnet assembly angle of -36° was used. Experimental evaluation is made using Umetrics Modde 11 (www.umetrics.com).

Table 8. Factor levels of the designed experiment used in the bench scale wet LIMS. A more detailed description can be found in Paper IV.

<table>
<thead>
<tr>
<th>Level</th>
<th>Low level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed solids concentration</td>
<td>4.5 vol% solids (19 wt%)</td>
<td>9.7 vol% solids (35 wt%)</td>
</tr>
<tr>
<td>Drum rotational speed</td>
<td>43 rpm</td>
<td>74 rpm</td>
</tr>
<tr>
<td>Slurry feed rate</td>
<td>19 dm³/min</td>
<td>42 dm³/min</td>
</tr>
<tr>
<td>Magnet assembly angle</td>
<td>-42°</td>
<td>-36°</td>
</tr>
</tbody>
</table>

Between each run the drum rotation and the feed pump is stopped and all factors are changed manually. The feed solids concentration was achieved by mixing tap water and magnetite in the mixing tank. The drum rotational speed is controlled by a mechanical lever on the driving motor. The slurry feed rate is computer-controlled via the AC-drive. The magnet assembly angle is adjusted by moving a mechanical lever between two end positions.
5.5. Experiments in the pilot scale wet LIMS

In the pilot scale experiments the ultrasound based methods used in the bench scale separator are adapted to pilot scale, see Figure 22. The magnetic separator is run at realistic conditions, and a pair of transducers is used to monitor the internal flow in two positions in the concentrate dewatering zone. The measurements are made after the separation process has reached steady state (120 s). Measurement system properties are listed in Table 5, column 5.

Between each run the feed pump and the drum rotation is stopped and all factors are adjusted manually. The desired feed solids concentration is achieved by mixing tap water and magnetite in the pump sump, and the stated solids concentrations were measured by sampling the feed stream and drying the sample. The drum rotational speed is controlled by an AC drive (ABB ACS800, www.abb.com), and the specified speed is measured, without separator material loading, using a handheld laser tachometer. The overflow weir distance is adjusted manually and measured with a plastic gauge block. The magnet assembly angle was adjusted manually between three levels. The stated magnetic pole positions were approximated using a steel blade (as in Paper IV). On the high factor level the magnetic pole closest to the concentrate discharge is aligned with the overflow weir. For the low factor level the pole is 20 mm below the overflow weir. The difference between the high and the low level, 20 mm at the drum periphery, corresponds to a change in magnet assembly angle of 2.5°.

5.5.1. Design of experiment

The investigation is carried out as a designed experiment, a 2-level factorial design of four factors. The factors included are the feed solids concentration, drum rotational speed, overflow weir, and the magnetic assembly angle, see Table 9. Additionally measurements were in two positions in the separator tank bottom, and using two relative transducer inclination angles. Experimental evaluation is made using Umetrics Modde 11.

Table 9. Factors and levels used in the designed experiment in the pilot scale wet LIMS, see also the separator sketch in Figure 22.

<table>
<thead>
<tr>
<th>Level</th>
<th>Low level</th>
<th>High level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed solids concentration (feed)</td>
<td>5.5 vol% solids (23 wt%)</td>
<td>11 vol% solids (38 wt%)</td>
</tr>
<tr>
<td>Drum rotational speed (drum)</td>
<td>5.7 rpm</td>
<td>29.5 rpm</td>
</tr>
<tr>
<td>Overflow weir distance (weir)</td>
<td>10 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>Magnet assembly position (mag)</td>
<td>-20 mm</td>
<td>0 mm</td>
</tr>
<tr>
<td>(pole distance below weir)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor position (pos)</td>
<td>Towards feed entry</td>
<td>Towards conc. discharge</td>
</tr>
<tr>
<td>Transducer rel. inclination angle (angle)</td>
<td>60°</td>
<td>90°</td>
</tr>
</tbody>
</table>
With this experimental setup it was not feasible to vary the feed solids concentration independently. To still get some indication of the repeatability of the measurements it was assessed separately for each of the two concentration levels, at both transducer positions and at both transducer inclination angles. For both levels of solids concentrations, the measurements were made three times; in the beginning, middle, and in the end of the series, with the remaining factors at their centre levels. At the centre level a drum speed of 17.6 rpm, an overflow weir distance of 20 mm, and a magnet assembly position 10 mm below the weir was used.
Wet low-intensity magnetic separation: Measurement methods and modelling
In the first part of this chapter the results from the appended papers are summarized. In the following sections some of the results from the experiments are highlighted, divided by the type of experiment.

In paper I the robustness of the UVP method is investigated in flow of magnetite suspension with a solids concentration of 5 vol% solids. Three methods for combining repeated flow profile measurements are evaluated; these are the arithmetic mean, weighted mean, and median filtering. The arithmetic mean starts to deviate from the expected profile first. To some extent this is avoided by placing more trust in strong correlating measurements using the weighted mean. In the presented experiments the median filtering is the least sensitive to low signal strength.

In paper II the performance of four transducers are evaluated in flow conditions relevant to wet LIMS; magnetite suspension with solids concentration of 5 vol% and 9 vol% solids. It was found that the most reliable measurements were produced with the 2.25 MHz transducer, reaching through the whole depth of 50 mm. For the 3.5 MHz transducer the penetration depth was approximately 30 mm, and the pulses from the 1 MHz transducer did not interact enough with the suspension to create backscattered signals of high enough contrast, resulting in increased uncertainty in the flow velocity profile estimation.

In Paper III it is demonstrated how a short-time (windowed) PSD estimate can be used to obtain qualitative information about local solids concentration variations. Magnetite suspensions carrying up to 7.5 vol% particles are pumped through the rectangular flow cell, and when the pump is stopped, pulse-echo ultrasound is used to monitor the settling process. It is clear that the short-time PSD is a good indicator of local variations in solids concentration.

In paper IV the methods presented in Paper I - III are adapted to a bench scale separator. The UVP method is also extended to estimate local particle velocity in two dimensions. The methods are evaluated in realistic conditions, where the effect of varying factors relevant to machine performance is investigated. The included factors are the slurry feed rate, slurry solids concentration, magnet assembly angle, and the drum rotational speed.

In paper V the process of magnetic capture of particles are studied on small scale, using the Stokesian dynamics method. Stokesian dynamics is a mesh-free numerical technique developed for particle suspensions. The implementation created here allows for simulation of the motion of suspended magnetic particles in presence of an external magnetic field. The magnetic interaction model includes particle-field interactions as
well as pairwise interactions between magnetized particles. Models are based on the magnetic capture experiments presented in Paper VII. The numerical simulations capture effects important to magnetic separation, and can therefore be used for improving the understanding and predicting the efficiency of mineral separation processes.

In paper VI the measurement methods developed in Paper IV are evaluated in real world conditions in a pilot scale concentrator. The system is installed and evaluated in a wet LIMS at the LKAB R&D facilities in Malmberget, Sweden. The internal material transport is monitored. Changes to operational conditions are reflected in the velocity and concentration measurements.

In paper VII the measurement methods studied in Paper I, II, III and VI are summarized and the results are reported from the flow measurement and signal processing perspective.

1 Measurements in undisturbed flow in the flow cell (Paper I, II, VII)

In the experiments in undisturbed flow the 1D UVP method is used to measure particle velocity in suspension flow in the rectangular flow cell. The performance is evaluated in varying flow conditions. The factors included are the suspension solids concentration, mean flow rate, and the transducer centre frequency. With these experiments the accuracy of the method is studied in controlled conditions in a simple geometry. Below selected results are presented.

To assess the quality of the measurements the results are compared to numerical simulations, see Figure 28. In the model a geometry with the same dimensions as the flow cell is used, and a 1 m/s flow of water is simulated. The basic computational fluid dynamics (CFD) simulation is done in Comsol Multiphysics 4.3 (www.comsol.com). The

![Figure 28](image-url)

Figure 28. Particle velocity profiles measured in suspensions of low solids concentration; < 0.5 vol% solids (dashed black) and approximately 2 vol% solids (black). Measurements are compared to CFD simulation (thick blue). The transducer is located above the figure. On the vertical axis, 0 and 50 mm represent the top and bottom of the flow cell, respectively.
The $k$–$\varepsilon$ turbulence model is used and all other settings are left at their defaults. When compared to measurements at low solids concentration, 2 vol% solids or less, the measurements and the simulation were in good agreement.

In Figure 29 the measurement system performance is evaluated in suspension with a solids concentration of 5 vol% solids, corresponding to 20 wt% solids. 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 approximately 27 mm is reached for the 3.5 MHz transducer and approximately 22 mm for the 5 MHz transducer. In the combination of flow conditions, solids concentrations, and particle size distribution used in this work, the pulses from the 1 MHz transducer did not interact with the suspension to an extent sufficient for producing backscattered signals of high enough contrast. This resulted in increased uncertainty in the flow velocity profile estimation. When the concentration is increased to 9 vol% (33 wt%) the 2.25 MHz transducer still produces the most reliable results and it is possible to reach a depth of almost 30 mm (see Paper II). Based on these results the 2.25 MHz transducer was used in the experiments in realistic geometries. Measurement system properties are listed in Table 5; column 1a is used in Figure 29a–b, and column 1b in Figure 29c–d.

**Figure 29.** Measurements on flow of magnetite suspension (5 vol% solids) at bulk flow velocity of 0.75 and 1 m/s, four transducers are compared. The transducer is located above the figures. On the vertical axis, 0 and 50 mm represent the top and bottom of the flow cell, respectively.
For the method used in these experiments the estimation of measurement uncertainty is problematic. A flow velocity profile can successfully be estimated, but the standard deviation of the associated data is relatively large. However, the standard deviation has two sources, both the measurement error and the random fluctuations of turbulence. In Figure 30 repeated UVP-measurements are made (at 800 Hz) in a turbulent suspension flow. Each vertical line represents one independent measurement, coloured by local particle velocity. A transducer with centre frequency of 3.5 MHz, sampling frequency of 200 MHz, pulse repetition frequency of 8 kHz, and a window length of 3100 samples was used. The figure illustrates the effect of turbulence on the standard deviation of the measured velocity at a certain depth. This velocity varies considerable with time, due to measurement error, but also due to turbulence. If variations were only due to random measurement error, consecutive measurements would not be related, and variation over time would not be so smooth, see also Figure 4.

Figure 30. Suspension particle velocity field composed by repeated UVP measurements. The bulk flow velocity is 0.7 m/s, and the suspension solids concentration is 2 vol% solids. The transducer is located above the figure. On the vertical axis, 0 and 50 mm represent the top and bottom of the flow cell, respectively.

2 Measurements in settling suspension in the flow cell (Paper III, VII)

In the experiments with settling suspension the PSD is used to get qualitative information about variations of solids concentration in settling suspension in the flow cell. The possibilities to track changes in local solids concentration are evaluated in realistic conditions. Since the measurements are made in controlled conditions the general outcome of the settling experiments are known, and measurements can thus be compared to theory.
Nine snapshots of a settling process are shown in Figure 31. The backscattered signal is acquired at a pulse-repetition frequency of 200 Hz, to be able to study rapid variations in local solids concentration. Measurements are made using a 3.5 MHz transducer during 10 s, and the snapshots are calculated as the mean PSD over 40 measurements (0.2 s). The first snapshots, in the top row (Figure 31a, d, and g), are taken just shortly after the pump begins to decelerate (at time $t_0$). Then there is a time lapse ($\Delta t = 5$ s) between the images, showing the settling process, e.g.; Figure 31a–c for the 7.5 vol% solids case.

![Figure 31. Backscatter PSD for three solids concentrations at three times during suspension settling.](image)

The transmitted ultrasound pulse will naturally create a backscatter spectrum with highest intensity around its centre frequency. Low local solids concentration gives less backscatter, and a lower intensity. By interpreting this information it is possible to qualitatively follow variations in local solids concentration, as function of depth and time. An increase in backscattered intensity indicates an increase in solids concentration, e.g; when the transmitted pulse reaches the settling interface the locally increased solids concentration creates a strong echo. If the settling suspension has become of high solids concentration the signal is then strongly attenuated.

By using the described method it is possible to qualitatively follow variations in local solids concentrations, as a function of depth and time, for suspensions with a wide range of solids concentrations. In a settling suspension it is possible to follow the settling interface, e.g. the arrows in Figure 31b, e, and h. As expected, the settling velocity varies with particle concentration, due to e.g. hindered settling.
3 Measurements and simulation of magnetic particle capture (Paper V, VII)

In the magnetic particle capture experiments a set of magnets is added to the rectangular flow cell, and the ultrasound system is used to monitor the build-up of magnetic material at the top wall of the flow cell. The effects of varying the suspension solids concentration, magnetic field strength, and the suspension flow rate are studied. In the closed geometry of the flow cell the velocity profile gives a clear indication of how thick the magnetic build-up is, since the suspension flow is diverted downwards by the stationary magnetic build-up, see Figure 32a. This is, however, not the case in the wet LIMS, where the complex geometry and rotating drum allows for the flow to simultaneously have low velocity and low solids concentration. Therefore it is of interest to monitor the build-up thickness using information extracted from the backscatter signal PSD, see Figure 32b. In the flow cell the velocity measurements can be used for validation of the concentration measurements.

For the measurements in Figure 32 the solids concentration was 0.78 vol% solids, the bulk flow velocity was 0.75 m/s, and the magnets were added a distance of 22 mm from the flow. A transducer with centre frequency of 3.5 MHz was used, and Figure 32a was generated using the same method as Figure 30. The mean PSD was averaged using all frequencies in the range from $0.5f_c$ to $2f_c$.

![Figure 32](image)

Figure 32. The process of magnetic build-up monitored using a) velocity measurements, and b) mean PSD measurements. The magnet assembly is placed on top of the duct at time $\approx 4$ s. a) Velocity, b) Mean PSD. The transducer is located below the figures. On the vertical axis, 0 and 50 mm represent the bottom and top of the flow cell, respectively.

3.1 Estimating the steady state build-up thickness

In this part the mean backscatter PSD is used to estimate the steady state build-up thickness of the magnetic cake created in the flow cell by the magnet assembly. In Figure 33 three examples with varying magnetic field strength are shown. The suspension solids concentration is 1.4 vol% solids, the mean flow velocity is 0.75 m/s, and a transducer with centre frequency 2.25 MHz is used.
In Figure 33, the middle subfigures show the mean backscatter PSD, calculated as the mean of the PSD, both over time, and over frequencies between $0.5f_c$ and $2f_c$ (basically the time-average of the right third of Figure 32b). The subfigures to the right show the space-derivative of the mean PSD (in the middle figures). To make the figures more clear the derivative is filtered using a moving average filter. The horizontal red dashed lines mark the approximate position of the transition between suspension flow and magnetic build-up. The line is positioned where the mean PSD starts to increase, seen from the transducer, in the subfigures to the right.

The magnitude of the increase in mean PSD, marking the transition into the magnetic build-up, is calculated using the following procedure. The build-up is assumed to be between 10 and 40 mm thick. A high level of increase in the mean PSD is calculated as the maximum increase in the depth-span of interest; 10-40 mm. A low level of increase in the mean PSD is calculated as the maximum increase in the depth-span 0-10 mm. Finally the limiting increase of the PSD is set in the middle between these two values. The depth where this limit is first reached, seen from the transducer, is considered the position of the magnetic build-up.

For comparison, the suspension velocity profile measured during steady state is included in the left subfigures of Figure 33 (basically the time-average of the right third of Figure 32a). One standard deviation in the measurement (partly due to turbulence) is also included (dashed green).

### 3.1. Factors affecting ultimate build-up thickness

By estimating the thickness of the magnetic build-up, as in the figure above, it is possible to study how the layer thickness is affected by a change in; the feed solids concentration (4 levels), magnetic field strength (3 levels), and the suspension flow rate (3 levels). This has been done for all combinations of the factors and levels in Table 10. To be able to get some indication about the repeatability of the method, the combination of flow velocity level #2 and field strength level #2 was run three times for each level of solids concentration. The method is reasonably robust; out of the total of 44 runs, only three at the highest level of solids concentration, and one at the second highest level of solids concentration, had to be rejected. These were excluded from the statistical calculations presented below.

<table>
<thead>
<tr>
<th>Level</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed solids conc. (vol%)</td>
<td>0.23 vol%</td>
<td>0.78 vol%</td>
<td>1.4 vol%</td>
<td>2.8 vol%</td>
</tr>
<tr>
<td>(Transducer, $f_c$)</td>
<td>(3.5 MHz)</td>
<td>(3.5 MHz)</td>
<td>(2.25 MHz)</td>
<td>(2.25 MHz)</td>
</tr>
<tr>
<td>Mean flow velocity (m/s)</td>
<td>0.5 m/s</td>
<td>0.75 m/s</td>
<td>1.0 m/s</td>
<td>-</td>
</tr>
<tr>
<td>Mag. field strength (mT)</td>
<td>(45.5 mT)</td>
<td>83.5 mT</td>
<td>166 mT</td>
<td>-</td>
</tr>
<tr>
<td>(Spacer distance)</td>
<td>(32 mm)</td>
<td>(22 mm)</td>
<td>(12 mm)</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 33. Profiles showing flow velocity, mean of PSD, and change in mean PSD, for varying magnetic field strength. The horizontal dashed lines mark the approximated positions of the transition between suspension flow and magnetic build-up. The magnets are located above the figures, and the transducer is located below. In the velocity plots to the left one standard deviation of the velocity measurements (partly due to turbulence) is included (dashed green). On the vertical axis, 0 and 50 mm represent the bottom and top of the flow cell, respectively.
As seen from Figure 34, an increase in magnetic field strength has a positive effect on the build-up thickness, as expected. An increase in flow rate has a negative effect on the build-up thickness; this is also expected, since an increased flow rate gives an increased pressure on the build-up. Lastly, an increase in the suspension solids concentration has a positive effect on the build-up thickness.

One possible explanation is that the increased build-up thickness is created by increased magnetic flocculation because of the higher solids concentration. However, it could also be a measurement error caused by the decreased difference in solids concentration between the suspension flow and the magnetic build-up. With this material the magnetic build-up is expected to have a solids concentration of approximately 35 vol% solids (70 wt% solids, Rayner and Napier-Munn, 2003a). With increased solids concentration in the suspension flow the difference between the flow and the build-up is reduced. These experiments show that backscatter PSD can be used to monitor the thickness of magnetic build-up. However, for this method to work there has to be a distinct difference in the solids concentration of the flowing suspension and the stationary build-up.

Figure 34. Factor effects on magnetic build-up thickness during steady-state flow. The factor abbreviations are explained in Table 10.

3.2. Simulating the magnetic particle capture process

Simulating the wet LIMS, or even one of the simplified systems described above, is a challenge, especially if the results need to include particle effects. The main issue is the vast number of particles. The volume of a 35 µm particle is $2.2 \times 10^4$ µm$^3$, and a volume of only 1 cm$^3$ with a suspension of 5 vol% solids, will contain over 2 million of these particles.

In Paper V a Stokesian dynamics-based simulation framework is presented. The purpose is to combine the accuracy of suspension-oriented particle methods with the efficiency of a simplified mesh-free mathematical approximation of the magnetic field and fluid flow. To achieve reasonable simulation times the number of particles is kept low, and thus only a small volume is simulated. To limit model complexity laminar flow is assumed.
The model includes hydrodynamic and magnetic forces only; by restricting particle size to 2 µm it is possible to neglect the gravitational forces. In Figure 35 a result from a simulation of a suspension with 1000 magnetic particles and 1000 non-magnetic particles are shown. Magnetic particles are attracted towards a stationary magnetic pole (M).

Two mechanisms that could result in particle entrainment were observed. In the first mechanism a non-magnetic particle follow the magnetic particles towards the magnetic source, affected by hydrodynamic or frictional forces. The second mechanism entails that non-magnetic particles follow the fluid flow until they get trapped by the cluster of magnetic particles near the magnetic pole. Then, suspended magnetic particles approach from behind and lock into the magnetic floc, and the non-magnetic particle becomes completely surrounded. It is possible that these two mechanisms could exist at the same time, both contributing to the capturing of non-magnetic particles.

In addition to particle entrainment, the simulation also shows magnetic flocculation effects, where flocs orientate in the direction of the flow. This magnetic flocculation is a result of particle magnetization and consequently attraction of particles to each other in the vicinity of the magnetic pole. Small magnetic flocs appear, under some conditions, to be able to eventually detach from the structure as seen in subfigures e) and f).

Figure 35. Motion of 2 µm magnetic particles (dark) and non-magnetic particles (light). The direction of the parabolic flow is indicated in a). M indicate the position of the fixed magnetic pole. The simulation time is included above the figures. The later time steps show entrainment in the particle clusters near the magnetic pole.
4 Measurements in the bench scale wet LIMS (Paper IV)

In the bench scale experiments two ultrasound transducers are fitted to the tank of a wet LIMS and used to monitor the internal flow in the concentrate dewatering zone. 2D UVP is used to capture internal velocity profiles. Simultaneously, the backscatter signal intensity is used to get information about the local solids concentration of the flow, and the build-up of magnetic material on the drum. The methods are evaluated in realistic conditions, where the effect of varying factors relevant to machine performance is investigated. Four factors relevant to separator performance are evaluated in Paper IV, in Figure 36 and Figure 37 the two extreme cases are presented. The low feed solids concentration together with the low feed rate provides the lowest solids feed rate. The high drum speed together with the high magnet assembly angle should provide the most efficient material removal from the concentrate dewatering zone. This extreme is shown in Figure 36, and the opposite case is shown in Figure 37.

![Ultrasound measurements and a photograph showing the bench scale separator operated at low material load.](image)

a) Backscatter amplitude measured along the vertical dashed line in c), showing variations over time. b) Backscatter amplitude measured along the inclined dashed line in c), showing variations over time. c) Flow velocity pattern, drawn on a 2D cross section of the separator geometry, showing the concentrate dewatering zone. d) Photograph taken from the side of the separator, showing approximately the same area as c).

Figures a) and b) show the backscatter signal intensity, as a function of depth and time. For the first case the signal is attenuated smoothly with distance from the transducer, indicating homogeneous flow of low solids concentration. The variations in backscatter intensity with time indicate the presence of rapid concentration variations in the
monitored zone; maybe magnetic flocs extending from the drum. For the high load case most of the dewatering zone is packed with magnetite, indicated by the strong signal attenuation. Figures c) show the velocity patterns captured using 2D UVP method. In the low load case a profile showing a recirculating flow is captured. For the high load case the signal is severely attenuated, and thus the flow profile should be ignored. Figures d) show images (extracted from the videos) captured through the transparent wall of the separator, in approximately the same area as the velocity measurements. For the low load case the video shows a small magnetic build-up near the concentrate discharge. For the high load case the overload situation is confirmed by the video.

The presented method gives useful information about the internal material flow inside the separator. The velocity measurements capture the internal flow patterns, for example the presence and velocity of a recirculating flow in the dewatering zone. Additionally, keeping a balanced material loading in the concentrate dewatering zone is important to separator performance. By using the signal backscatter intensity it is possible to qualitatively monitor this material loading.

Figure 37. Ultrasound measurements and a photograph showing the bench scale separator operated at high material load. a) Backscatter amplitude measured along the vertical dashed line in c), showing variations over time. b) Backscatter amplitude measured along the inclined dashed line in c), showing variations over time. c) Flow velocity pattern (showing unrealistic flow profile), drawn on a 2D cross section of the separator geometry, showing the concentrate dewatering zone. d) Photograph taken from the side of the separator, showing approximately the same area as c).
5 Measurements in the pilot scale wet LIMS (Paper VI, VII)

Particle velocity and concentration measurements are made on the concentrate side of a pilot scale wet LIMS. Since the relative difference in the relevant dimensions between the pilot scale and the full scale separators are small, the results are relevant also to full scale separators. The effects of varying four factors important to process operating conditions are studied. Below measurements of flow velocity and magnetic build-up is presented for selected cases, together with the effects of varying the factors in Table 9.

Figure 38 shows the estimated particle velocity vectors for four combinations of operational settings. At the low drum speed, in Figure 38a-b, the material removal rate is limited, leading to build-up of magnetic material. This build-up diverts the suspension flow, leading to velocities of varying direction and magnitude. In Figure 38c-d the drum speed is at its high level, resulting in limited material build-up and an increased flow rate in the direction opposite to the drum rotation. It is likely that the high drum rotational speed brings more water into the dewatering zone, and that the increased return flow is seen in Figure 38c-d.

![Figure 38](image-url)

Figure 38. Internal flow patterns from pilot scale wet LIMS. Flow velocity patterns are drawn on a 2D cross section of the separator geometry, showing the concentrate dewatering zone (the drum radius is 450 mm). Flow velocity profiles are measured using a 60° inclination angle (green arrows) and 90° angle (blue arrows) between the transducers. a) All factors at their low level. b) High feed solids concentration, remaining factors at their low level. c) Low feed solids concentration, remaining factors at their high level. d) All factors at their high level.
In some cases, e.g. Figure 38c, there are notable deviations between the measurements at the two relative sensor angles (60° and 90°). These are, however, believed to be mainly due to experimental error in the control of the separator. Controlling the separator and achieving repeatable conditions are a challenge, since the pump and the separator are stopped, and the sensor positions are changed manually between each measurement.

Figure 39 shows the backscatter PSD, for the wave paths labelled (I)-(IV) in Figure 38. In all cases the backscatter amplitude decays as function of depth. For a homogeneous suspension of low solids concentration this decay is expected to be linear (in the dB scale) due to the exponential nature of ultrasound attenuation, see e.g. Carlson and Martinsson (2002). The suspension below the magnetic build-up at the drum is expected to have low solids concentration, since only non-magnetic particles (with very low concentration in the feed material) should be in this zone. In cases I and II in Figure 39, the decay of backscatter amplitude is non-linear. The strong increase in backscatter intensity 65 mm from the transducer in case I, and 30 mm from the transducer in case II, indicate the approximate position of the magnetic build-up on the surface of the rotating drum. In case II this material build-up is significantly thicker, which is expected since the solids concentration of the feed is higher than in case I.

In cases III and IV, the rotational speed of the drum was set to the high level, which should increase material removal rate and prevent material build-up. Flow velocities of approximately 0.5 m/s suggest a turbulent flow mixing the suspension, and as a consequence, the suspension solids concentration is more homogeneous. Also, since the magnetic particle build-up will be much thinner when the drum rotational speed is high, it is not visible in the figures.
In these experiments no evaluation of the actual separation results has been done. However, operating the separator using the factor levels used in e.g. case IV is likely to result in a bad separation result. If the concentrate dewatering zone is packed with solid material it is likely to prevent concentrate dewatering, leading to a wet, and less clean concentrate.

5.1. Factor effects on velocity profiles

To investigate the relationships between four separation process variables, and the measured velocity patterns, three response variables are calculated. The factors included are the suspension solids concentration, magnet assembly distance, overflow weir distance, and the drum rotational speed. Also, the sensor position is included in the model. The factor levels can be found in Table 9.

The first response, the mean flow in Figure 40, is the calculated mean flow velocity in the concentrate dewatering zone, projected on a line tangential to drum, and averaged over the whole distance between the drum and the tank bottom. Flow towards the concentrate discharge (upwards) is counted positive. For this response variable the relationships are mostly linear. The drum rotation speed is the factor having the strongest influence. This is likely since an increased drum rotation brings more water to the dewatering zone, and this water is then sensed as it is returning towards the feed entry (downwards flow, counted negative). Remaining effects are difficult to interpret.

Figure 40. Factor effects in the mean flow velocity in the concentrate dewatering zone of a pilot scale wet LIMS. The factor levels and the abbreviations can be found in Table 9.

Calculating the mean flow velocity in a specified direction is simple. In this case, however, interpreting the results becomes difficult, since several phenomena are grouped in one response. To improve the results the overall mean flow velocity is divided into two parts. The part of the flow going downwards (recirculating) is averaged in a one response; flow, down in Figure 41. The part of the flow going upward (towards the concentrate discharge) is averaged in a second response; flow, up in Figure 42.

In Figure 41 the factor effects on the downwards flow velocity are presented. Also for this response variable the relationships are mostly linear. As in Figure 40, and for similar
reasons, the drum rotational speed has the strongest influence. Also the magnet assembly
angle have a significant effect on the downwards flow; lifting the magnet assembly
increases the recirculating flow (downwards flow, counted negative), presumably because
the point where the flow turns is lifted out of the measurement zone.

In Figure 42 the factor effects on the mean upwards flow velocity are presented. For this
response variable the feed solids concentration and the drum rotational speed have the
strongest influence. Increased solids concentration is expected to increase the flow
towards the concentrate discharge, since more magnetic solids need to be transported in
that direction. As for the prior responses, an increased drum speed has a negative effect
on the mean flow velocity.

Also the sensor position has significant effects, both linear and as an interaction effect
with feed solids concentration. Studying the relevant flow patterns, the measured
upwards flow velocity is notably higher in the sensor position towards the feed entry
when the feed solids concentration is high. The reason is that, when the feed solids
concentration is high, a fast upwards flow is sensed in the position closest to the feed
entry. When the feed solids concentration is low, and in the other sensor position, the transportation of magnetic material is more concentrated towards the drum, resulting in a lower measured average velocity.

Initially the transducer relative inclination angle was also included in the described models. It was, however, removed since it had no significant effects. This absence of significant effects indicate that, in the present conditions, both relative inclination angles (60° and 90°) give similar results when estimating the mean flow velocity.

5.2. Influence of separator size on measurement performance

In the presented results two separators are used, with drums of Ø200 mm and Ø916 mm. In industry, separators with drums of Ø1200 mm are the most common. The 2D UVP method was initially developed for the bench scale separator (Ø200 mm). When adopting the system to the pilot scale separator (Ø916 mm), it was believed that the increased measurement depth and the possible presence of air-bubbles in suspension would make it a more challenging environment. However, the performance was actually improved, and the reasons are believed to be:

- More advantageous relation between measurement depth and transducer diameter, for the bench scale separator the measurement depth was only 2-3 times the transducer diameter, making the interaction volume relatively large
- The strong segregation of particles in the tank (by the magnetic attraction from the magnet assembly) makes sound attenuation lower in a considerable part of the flow closest to the sensor
- The amount of air bubbles in suspension was found to be lower than expected. In bench scale this can be controlled to some extent, but in pilot and full scale the conditions more or less have to be accepted as is.

During this work it was not possible to test the measurement methods on Ø1200 mm separators. However, in terms of measurement depth the difference from a Ø916 mm separator is relatively small (only 30% based on drum diameter). Based on this small difference it is likely that the methods will work also in full scale separators. The PRF and sampling time need to be adjusted to achieve a deeper measurement depth. Also, it is not necessary to reach through the whole depth of the tank to gain valuable information.
Wet low-intensity magnetic separation: Measurement methods and modelling
During this work several aspects of wet LIMS have been studied, with focus on the complex internal material transport processes inside the separators. State-of-the-art measurement methods have been utilized to monitor material flow in the separators. Particle capture and entrainment have been studied on the particle level using numerical modelling. Measurement results have been linked to operational conditions of the separators. The insights gained, and the methods developed, has generated new possibilities to control, optimise, and develop the wet LIMS process.

1 Ultrasound based measurement methods in wet LIMS

The major part of this work has been focused on finding measurement methods suitable for internal measurements in the wet LIMS process. Two ultrasound based measurement methods were selected, combined, and improved. The methods were then evaluated in conditions relevant to the separation process. With the first method, the local suspension velocity is measured in one and two dimensions, in a range of flow conditions. The second method reuses the measured data from the first method to obtain qualitative information about variations in the local solids concentration. By using the same data both methods can be utilized simultaneously.

After doing extensive measurements in a wide range of flow conditions it can be concluded that the method is versatile and can be adapted to handle a range of environments. One of the main strengths of the method is that the equipment is small and flexible. Measurements can be done from a single point of access, making the method flexible as the sensors can be fitted in various positions in different equipment. The transducer diameter used here is \( \text{\textvar{13 mm}} \), which would allow two (or possibly three) sensor to be mounted together at the required inclination angle in a module with a diameter of approximately \( \text{\textvar{100 mm}} \).

The measurements are fast; the measurement time is governed completely by the speed of sound in the suspension (\( \text{\textvar{1500 m/s}} \)). For instance, a depth of 0.75 m is covered in 1 ms, and by repeating the measurements a few hundred times, high precision can be achieved. Another notable strength with the presented approach is that both velocity and concentration measurements can be made simultaneously, in the same volume of suspension. This simplifies sampling, signal processing, and presentation of the data.

The main limitation regarding ultrasound based methods are the need to match the transducer centre frequency to the suspension to be monitored. Low sound frequencies interact less with the suspension, and thus penetrate deeper into the suspension, but give
a weaker backscatter signal. There has to be a balance between the signal attenuation and backscatter signal strength; the signal need to penetrate through the whole suspension volume of interest, while simultaneously giving a sufficiently strong backscatter to allow for successful signal processing. Also the performance of the methods is adversely affected by high solids concentration and air-bubbles in suspension.

1.1. **Velocity measurements**

During this work it has been shown how flow velocity profiles can be estimated with sufficient precision in wet LIMS. The methods are versatile; measurements can be done in suspensions of very low solids concentration, and for short distances solids concentration of at least 10 vol% solids can be handled. The velocity measurements capture the, sometimes complex, internal flow patterns of the wet LIMS, e.g. the presence (and local velocity) of a recirculating flow in the dewatering zone is shown. This dewatering flow is found to depend mainly on the drum rotational speed, where a high drum speed gives an increased dewatering flow rate. In Figure 40 to Figure 42 it is shown that the measured velocity patterns show significant correlation with operational factors of the separator.

1.2. **Concentration measurements**

During this work it has been shown how information about local solids concentration can be extracted from a backscattered ultrasound signal. Variations in the suspension solids concentration are seen as gradients in the backscatter PSD. With the presented methods it is possible to acquire qualitative information about material build-up inside the separator, and monitor internal material loading. In the industry this could be used to monitor loading conditions and prevent under/overload.

It should be noted, however, that the concentration measurements are qualitative. This means that local variations in solids concentration can be monitored, but neither the absolute concentration, nor the magnitude of the change can be calculated with any precision using available methods. For suspensions of low solids concentration (where single scattering can be assumed) there are methods available for both relative and absolute solids concentration measurements. Also if the suspension can be assumed to be homogeneous there are methods available for quantitative measurements. In the conditions relevant here neither can be assumed.

2 **Material transport inside wet LIMS**

During this work material transport is studied on a level of detail corresponding to the interaction volume of the ultrasound measurements. In the presented conditions this volume can be approximated as a cylindrical volume with a length of 10 µm, and a diameter of 10 mm. Any such volume inside a wet LIMS will contain a large number of particles, and thus conclusions are drawn on suspension level, rather than particle level.
The separator operational variables evaluated during this work, in bench and pilot scale, were:

1. Feed solids concentration
2. Volumetric feed rate
3. Drum rotational speed
4. Overflow weir distance
5. Magnet assembly angle (distance).

The first three factors can be grouped based on their influence on the feed and extraction of solids, and thus, the material loading in the separator. These factors are certainly important for separator throughput, but they also need to be in balance for the magnetic flocculation of the feed material to be efficient. Low solids feed rate in combination with high drum speed will result in minimal material build-up in the separator, which makes flocculation inefficient. High solids feed rate in combination with low drum speed will result in material overload in the dewatering zone (see e.g. Figure 37). This overload is likely to prevent concentrate dewatering and in extreme cases lead to concentrate being forced to the tailings.

The last three factors (again including drum rotational speed) can be grouped based on their influence on the concentrate solids concentration. The drum rotation has a significant effect on the flow rate in the dewatering zone (see e.g. Figure 40 to Figure 42). This can be both desirable and undesirable in the process; a high drainage rate is likely to give increased washing of gangue particles from the concentrate. On the other hand, if there is insufficient time for dewatering the concentrate will be more dilute, and more of the fine gangue following the water will end up in the concentrate.

The outcome could to some extent be controlled with the magnet assembly angle and the weir overflow distance. The magnet assembly angle controls how high the magnetic material is lifted by the magnets and the drum in the concentrate dewatering zone. A higher lift gives a more efficient material removal, and less material build-up. However, for the concentrate dewatering to be efficient a low magnetic field strength is need, since particles in a strong magnetic field holds more water (see Figure 3). Lowering the magnet assembly will lowers the magnetic field strength in the upper part of the dewatering zone. Regarding the overflow weir distance, a less tight setting will give a larger capacity for material throughput, but also a risk of a wetter concentrate.

3 Industrial relevance

The methods developed, the measurement results presented, and the conclusions drawn during this work could be used by process operators and equipment manufacturers to improve the performance of their processes and products.

3.1 Improved wet LIMS design

In a standard wet LIMS process, a number of machine settings and feed properties can be adjusted independently, e.g.; the magnet assembly angle, scavenger zone depth, overflow
weir distance, drum rotational speed, solids feed rate, and the feed dilution. One major issue with the current designs is that each of these settings affects more than one of the internal material transport processes in a wet LIMS; like throughput, material pick-up, scavenging, and concentrate dewatering. These dependencies make research, operation, and process optimization difficult. Another issue with the available separators are that the possibilities to control the separation of non-liberated particles and the cut grade are very limited. Garcia-Martinez et al. (2011) suggests that the magnetic flocculation and separation of magnetite fines should be realized in a very low-intensity field, in order to remove gangue minerals trapped in magnetite concentrates.

Current separator designs predate the introduction of computer aided design (CAD), CFD and FEM in the design processes of the equipment manufacturers. These tools could provide valuable insights regarding separator design. Thus there should be room for improvements; either as a whole new concept or as improvements to e.g. the tank and magnet assembly design. The measurement methods presented here could then be used to evaluate the effect of the design changes.

Unsuccessful tests with drums of Ø1500 mm have previously been made (Sundberg, 1998). Following the trends seen when moving from a drum with Ø916 to Ø1200, these larger drum separators would be able to handle a larger capacity per drum, thus lowering the cost per ton processed. Furthermore the cleaning capability would improve, since more magnet poles can be fitted, which would increase the number of turnings of the magnetic concentrate particles on the drum surface. Using available flow simulation tools, together with the measurement methods presented here, it might be worth revisiting the idea of a larger drum diameter and investigate why this increase in drum diameter was previously unsuccessful.

3.2. Improved wet LIMS operation

Utilizing the presented method several aspects of magnetic separation could be monitored in-line and the information could be presented to the plant control system. In-line process monitoring is likely to decrease process variations and prevent operating the process using faulty settings for longer periods of time. By reducing variations, the overall process performance is likely to be improved. In-line measurements enabled by the presented methods include:

- Monitoring of material build-up inside the separator
- Detect material overload in the concentrate dewatering zone
- Monitor solids concentration in the feed stream
- Monitor distribution of dilution water between parallel separators in a bank to detect problems with dilution water (see Eriksson, 2013).

Regarding individual machine settings, both Lantto (1977a) and Davis and Lyman (1983), found that the depth of the scavenger zone is an important factor controlling separator performance. An increased depth reduces the suspension flow rate in the zone, but on the other hand, the magnetic force in the bottom of the zone is also reduced.
Adjusting this distance can in some cases have a positive effect on the process. Additionally, according to Davis and Lyman (1983), the drum speed may be used to optimize separator performance. Drum speed can be adjusted to either maximize throughput, or to maximize concentrate solids concentration (and minimize fine gangue in the concentrate). Possibly, similar result can be achieved by adjusting the solids feed rate to match a set rotational speed. Furthermore, keeping a balanced material loading in the concentrate dewatering zone seems important to separator performance. Using a too low solids feed rate (low throughput) is also likely to give a concentrate of low solids concentration (and a wet concentrate will also be less clean). Overloading the separator, on the other hand, is likely to prevent washing of the concentrate, thus also leading to a less clean concentrate.

### 3.3. Method potential in minerals processing

From a more general point of view the described measurement methods could be used to monitor flow of opaque suspensions in narrow channels in various applications. When applied to flows of mineral suspensions with high solids concentration, the presented method is unique in combining:

- Simultaneous estimation of local particle velocity and concentration
- Operation by a single transducer (two for 2D measurements)
- Good spatial resolution
- Low flow disturbance
- Operation in opaque, relatively dense, suspensions
- Possibility to study dynamic processes (measurement rate > 1 kHz).

Even if the methods could only be used to monitor a small volume inside a process unit, the measurements could still provide valuable insight about the process. The presented measurement method could be used for internal measurements, process monitoring, process control, or validation of simulations in e.g.; hydrocyclones, inclined plate separators, and in dewatering/thickening.

The described Stokesian dynamics-based simulation framework could be used for extended studies regarding particle capture, build-up of magnetic flocs, and entrainment of non-magnetic particles. By modifying the model also effects of mixed particles, or particles of varying magnetic susceptibility, could be studied.
The methods presented herein for velocity and concentration measurements in mineral suspension could be used in various ways in the future, e.g. for extended measurements in wet LIMS, measurements in other process equipment, or for validation of continued numerical simulation.

For the continued study of wet LIMS, extended measurements could be made in full scale separators, or in other separator zones. For example, the method could be utilized to; monitor properties of the tailings stream, investigate if there are differences along the width of the drum, or study if there are variations over time in flow conditions during normal process operation.

As discussed above several factors affect the separation performance; any of these factors could be investigated further using an expanded designed experiment. If the concentrate stream were sampled and analysed, and complemented with internal ultrasound based measurements, it would be possible to recognise flow patterns prevalent during optimal separation conditions. Then the ultrasound measurements would add additional value to the process control. Additionally, the ultrasound-based measurements could be a complement to help interpret the response of the designed experiment.

In recent years the tools available for numerical modelling have improved markedly, and opened possibilities to do improved modelling of the wet LIMS. For full separator modelling, multi-phase flow (CFD) simulations are probably preferred. Using multi-phase modelling, several, or possibly all of the present phases could be included. Particle behaviour could to some extent be included using particle tracking. For simulating particle capture and liberation issues on the other hand, a discrete element based method is needed. These methods include e.g.; DEM, particle finite element method (PFEM) or extended modelling using Stokesian dynamics. Validated models could then be used to do virtual design changes to the process, and to optimize the process performance.


Wet low-intensity magnetic separation: Measurement methods and modelling


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Robust Estimation of Particle Velocity Profiles in High Concentration Magnetite Suspensions

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ABSTRACT: In the mining industry magnetite particles are transported in aqueous suspension through different stages of the process. In some stages it is of interest to monitor both the concentration and particle velocity profiles over a cross-section of the flow. In this paper an ultrasonic flow meter method based on cross-correlation of backscattered sound is presented. High solid particle content (e.g. 20-40 wt%) makes this challenging and therefore the emphasis lies on developing robust signal processing techniques for particle velocity estimation. The developed method is evaluated in laboratory experiments on flows in a rectangular duct. Transducers with centre frequency 1, 2, 4 and 5 MHz are evaluated in flows with a solid content of 20% by weight (4.7 vol% solids). Using the 2 MHz transducer a penetration depth of 50 mm is reached.

INTRODUCTION

In the mining industry, magnetite particles are transported in suspensions with water through different stages of the process. In some of these stages, it is of interest to monitor both the concentration and particle velocity profiles over a cross-section of the flow. In this paper a method is developed for applications in wet low-intensity magnetic separation, which is a process for winning of fine ferromagnetic particles from iron ore slurries. To obtain good quality data the following specification has been identified:

1. The sensor is required to operate from one direction only, since the separator design allows physical access to the flow from only one side.
2. A technique capable of penetrating opaque and attenuating suspensions is required.
3. Some degree of spatial resolution is needed to interpret the results.
4. A non-intrusive technique is preferred since the internal environment is a very tough on equipment and also the best results are obtained if the flow is not disturbed.
5. Information about both flow speed and suspension concentration variations is desired.
METHOD

Here a speckle correlation technique, called Ultrasonic Velocity Profiling (UVP), is used. UVP monitors movements of local density differences in the flow. The method is summarised in the Signal Processing section and is evaluated in laboratory experiments where we measure on turbulent flow in a straight rectangular duct.

During signal processing it is assumed that the volume where the measured scatters originate, the interaction volume (IV), has a volume of negligible size. In reality this volume is finite, see Figure 1 and Jorgensen et al. (1973). As an approximation the IV can be seen as a cylinder shaped volume. Close to the transducer the diameter (d) is the same as the transducer diameter, further away the diameter increases as the pulse diverges (with divergence angle α). The height (h) of the IV is related to the ultrasonic pulse length and the speed of sound. Since the IV has a finite volume it will in some positions only partly be in the fluid flow, due to the inclined pulse path. This means that velocity profiles can become distorted close to walls; here approx. 5 mm from each wall.

![Figure 1. Cross section of the measurement duct showing transducer (TD) inclined at an angle β, ultrasonic pulse path, the concept of interaction volume and typical flow velocity profiles; laminar (L), turbulent (T) and plug (P) velocity profiles in steady uniform pipe flow.](image)

EXPERIMENTAL SETUP

The experimental setup has already been described by Stener et al. (2013) so only a short summary will follow. The setup consists of a closed loop made of rubber hosing with an internal diameter of 50 mm. The flow is driven by a progressing cavity pump capable of supplying an average flow rate up to 1 m/s in a rectangular measurement duct. The suspension temperature is stabilized by a heat exchanger fed with cold tap water.

The measurement section (height 0.050 m, depth 0.075 m and length 1 m) is made from 12 mm thick clear polycarbonate and the ultrasonic transducer is fitted at a 45° inclination at one end of the duct, see Figure 1. The length of straight duct in front of the transducer is 0.85 m (14 hydraulic diameters). The suspension consists of magnetite powder and tap water. The powder density is 5.0 kg/dm³, mean particle diameter is 34 μm and 85 wt% of the particles are smaller than 45 μm.

The measurements are made using four different immersion transducers from Olympus (www.olympus-ims.com) with centre frequencies 1.0 MHz (V303), 2.25 MHz (V306), 3.5 MHz (V382) and 5.0 MHz (V309). The transducers are controlled via a pulser-receiver (Panametrics 5800PR, www.olympus-ims.com). The 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 is measured using a digital thermometer (ASL F250 MKII, www.aslltd.co.uk).
SIGNAL PROCESSING

Assume that two backscatter signatures (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

\[
p_i[n] = p_i[nT_s], \quad i = 1, 2
\]

(1)

The two signals are acquired at a pulse-repetition frequency (PRF) so that the time between the two acquisitions is \( T_{\text{PRF}} = 1/\text{PRF} \). If the PRF is high enough, we can assume that the particles in the interaction volume (IV) has moved 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 \( T_{\text{PRF}} \). Finding this time delay can be done by a simple cross correlation of the two echoes, as

\[
n_0 = \arg \max_m \sum_{n=0}^{N-1} p_1[n] p_2[n - m],
\]

(2)

i.e. the time delay between the echoes is found at the lag \( m \) between the echoes that maximises the cross-correlation between them. Since the particle velocity varies throughout the flow this time delay will depend on the depth through the flow; displacement of the flow has to be considered a function of depth. Also, since the backscatter signatures will change slightly, the correlation between the entire waveforms will be rather weak. To overcome this, we therefore compute the cross-correlation between short segments of \( p_1[n] \) and \( p_2[n] \), thus resulting in one time delay estimate for each such pair of segments. In other words, let

\[
x_1 = \{p_1[1 + k], p_1[2 + k], \ldots, p_1[M + k]\}
\]

\[
x_2 = \{p_2[1 + k], p_2[2 + k], \ldots, p_2[M + k]\}
\]

(3)

be an \( M \) sample long window from \( p_1[n] \) and \( p_2[n] \), respectively, and let \( k = 0, 1, \ldots, N-M-1 \). For each value of \( k \), the time delay is then found as the lag maximising the cross-correlation function between \( x_1 \) and \( x_2 \). Once these delays have been determined, the particle velocity is computed as

\[
v[k] = n_0[k] \frac{T_s c}{T_{\text{PRF}} 2 \cos 45^\circ},
\]

(4)

where \( n_0[k] \) is the time delay for window position \( k \), \( T_s \) is the sampling time, \( c \) is the speed of sound in the fluid. The velocity is here projected onto the horizontal axis of the flow duct, using the inclination angle between the transducer and the flow, in this case 45\(^\circ\). To obtain better estimates of the particle velocity profiles, the above procedure is repeated 100 times, each resulting in an estimated velocity profile. These are then to be combined; the most obvious choice is to simply compute the arithmetic mean of all estimated velocity profiles, as

\[
v[k] = \frac{1}{100} \sum_{i=1}^{100} v_i[k].
\]

(5)

One problem is, however, that sometimes the velocity estimates fail, since the two backscattered echoes have decorrelated. Some method of suppressing these outliers is therefore needed. In this paper we evaluate two such approaches, the first being a weighted average
\[ v[k] = \frac{1}{\sum_{i=1}^{100} w_i} \sum_{i=1}^{100} w_i v_i[k], \]  

where \( w_i \) are the weights. These are chosen to be proportional to the correlation peak between \( x_1 \) and \( x_2 \), meaning that the average is weighted so that signals exhibiting more correlation are assigned a higher weight than signals that are weakly correlated.

The second alternative to the arithmetic mean is to take the median of the 100 velocity profiles. The median is known to be good at suppressing outliers, meaning that this should also efficiently discard estimates where the two signals have decorrelated. After averaging all flow profiles have been filtered with a moving average smoothing filter:

\[ v_i[k] = \frac{1}{2N+1} \{ v[k+N] + v[k+N-1] + \ldots + v[k-N] \} \]

RESULTS

Particle velocity profiles have been measured in flow of dense magnetite suspensions. In Figure 2 a selection of profiles are presented where a suspension carrying 20% solid particles by weight (4.7 vol% solids) have been used. The 2.25 MHz transducer produces the most reliable measurements. When the transmitting frequency is increased the signal is attenuated faster and does not penetrate the whole 50 mm; about 30 mm for 3.5 MHz and 20 mm for 5 MHz transducer. With the 1 MHz transducer a problem of using too low frequency is shown; this long wavelength (1.5 mm) does not create enough contrast for the cross-correlation process to produce a robust result.

DISCUSSION

As long as the strength of the backscattered signal is high enough all averaging methods produce similar results. The mean averaging (Eq. 5) starts to deviate from the expected profile first. To some extent this is avoided by placing more trust in strong correlating measurements using the weighted mean (Eq. 6). In these conditions the median averaging is the least sensitive to low signal strength and also produce results similar to simulation, see Figure 3.

The penetration depth of an ultrasonic pulse is mainly dependent upon ultrasound frequency (quadratic dependency), particle radius (cubic dependency) and mass fraction solids (linear dependency) (Carlson, 2010). When compared to other results in the literature (Stener et al., 2013) others have done deeper measurements and also in thicker suspensions, but not both at the same time. Also the majority of these measurements use transducers on both sides of the flow, which cuts the ultrasonic path in half.

During signal processing it is assumed that the speed of sound is the same as in water of the measured suspension temperature. Other investigators use different values; e.g. Wiklund (2008) uses 1530 m/s for mineral slurry at 20°C. But since the error in estimated flow velocity is proportional to the error in speed of sound the difference of using the speed of sound in water at 20°C instead of this higher value is only 3%.
Figure 1. Flow of magnetite suspension (4.7 vol% solids) at two different bulk flow speeds comparing three different transducers and three different averaging methods; mean (---), weighted mean (···) and median (−−−). The transducer is placed above the figures. The lines at 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.
As a comparison basic Computational Fluid Dynamics (CFD) simulations have been done 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 535·10³ elements. The \( k-\varepsilon \) turbulence model is used and all other settings are left at their defaults.

Figure 3. Left: Measured (and median averaged) particle velocity profiles where suspensions with low solid content is used; < 0.5 vol% solids (- -) and approximately 2 vol% solids (---). These are compared to a CFD simulation (---). Right: 2D cross-section from CFD simulation showing velocity contours [m/s].

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

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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 x 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% 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.

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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 titano-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.
Recently Dworzanski (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 and drum/tank distance.

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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. Hamberger 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 ultrasonic 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 is 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 \( \theta \) 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. Jørgensen et al. (1973) describe the IV as a 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 \( \alpha \)). 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 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.

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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 NM053BY011D68, www.netzsch.com) capable of supplying up to 14 m³/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

<table>
<thead>
<tr>
<th>Manufacturers-specified centre frequency (MHz)</th>
<th>Approximate wavelength (mm)</th>
<th>Divergence half angle</th>
<th>Near field (mm)</th>
<th>Part No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.50</td>
<td>8.1°</td>
<td>27</td>
<td>V303</td>
</tr>
<tr>
<td>2.25</td>
<td>0.67</td>
<td>3.6°</td>
<td>61</td>
<td>V306</td>
</tr>
<tr>
<td>3.5</td>
<td>0.43</td>
<td>2.3°</td>
<td>94</td>
<td>V309</td>
</tr>
<tr>
<td>5.0</td>
<td>0.30</td>
<td>1.6°</td>
<td>135</td>
<td>V309</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Property</th>
<th>Settings I(^a)</th>
<th>Settings II(^b)</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical measurement duct depth</td>
<td>50 mm</td>
<td>50 mm</td>
<td>Eq. (2)</td>
</tr>
<tr>
<td>Transducer inclination angle ((\theta))</td>
<td>45°</td>
<td>45°</td>
<td></td>
</tr>
<tr>
<td>Transducer nominal diameter ((d))</td>
<td>(\geq 13) mm</td>
<td>(\geq 13) mm</td>
<td></td>
</tr>
<tr>
<td>Sample frequency ((f_s))</td>
<td>400 MHz</td>
<td>200 MHz</td>
<td></td>
</tr>
<tr>
<td>Pulse repetition frequency (1/(T_{PRF}))</td>
<td>5 kHz</td>
<td>8 kHz</td>
<td></td>
</tr>
<tr>
<td>Measurements per flow profile ((N))</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Window length ((M))</td>
<td>1000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Vertical spatial resolution ((A_x))</td>
<td>2.7 (\mu m)</td>
<td>5.3 (\mu m)</td>
<td>Eq. (2)</td>
</tr>
<tr>
<td>Horizontal velocity resolution ((A_v))</td>
<td>13 mm/s</td>
<td>42 mm/s</td>
<td>Eq. (5)</td>
</tr>
<tr>
<td>Sound velocity in suspension ((c))</td>
<td>1480–1510 m/s</td>
<td>1480–1510 m/s</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) 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 5035, www.watson-marlow.com) is used. The flow rate (through a $\varnothing 1.5$ 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/dm³, 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.)](image)
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 P250 MDI, www.asltd.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), \( p[n] \) and \( p_2[n] \) are acquired by sampling the received analogue signals at a sampling rate \( T_s = 1/f_s \) so that,

\[
p_i[n] = p_i(nT_s), \quad i = 1, 2, \ldots, N
\]

(1)

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

\[
AY = \frac{cT_s}{2}
\]

(2)

where \( c \) is the speed of sound in the medium (calculated using measured temperature and standard data for water), \( \theta \) 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 \( \frac{1}{PRF} \). 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 (\( \tau \)) proportional to the movement of the suspension during the time \( \frac{1}{PRF} \).

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 \( m \) will carry information from different depth in the flow. By dividing the sampled signal into short segments,

\[
x_i[k] = \left[ p_1[k + 1] \ldots p_1[k + M] \right], \quad x_2[k] = \left[ p_2[k + 1] \ldots p_2[k + M] \right]
\]

(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 \( k = 0, 1, \ldots, N-M-1 \).

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

\[
XC(m, k) = \sum_{i=0}^{N-M} p_i[n]p_j[m-n]
\]

(4)

where \( m \) is a sufficiently large span of lags; e.g. \( m = -256, -255, \ldots, 0, 1, \ldots, 255, 256 \).

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

\[
\Delta v = \frac{T_c}{2} \frac{1}{2\sin \theta} \frac{1}{PRF}
\]

(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:

\[
n_i[k] = \frac{1}{2N+1} \left[ p[k - N] + p[k - N + 1] + \ldots + p[k + N/2] \right]
\]

(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
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 × 10^6 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 pulse-set-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. 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.

### 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% 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.

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### References


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**Table 3**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Solid material</th>
<th>Avg. particle dia. (μm)</th>
<th>Max. solids conc.</th>
<th>Max. penetration depth (transducer inclination angle)</th>
<th>Transducer centre frequency (MHz)</th>
<th>Transducer size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeda (1980)</td>
<td>Al₂O₃</td>
<td>5</td>
<td>Low</td>
<td>≥12 mm (45°)</td>
<td>4.2</td>
<td>≥4</td>
</tr>
<tr>
<td>Carlson and Ing (2002)</td>
<td>Magnetite</td>
<td>54</td>
<td>Low</td>
<td>≥15 mm (45°)</td>
<td>3.5</td>
<td>≥4</td>
</tr>
<tr>
<td>Wiklund and Stading (2008)</td>
<td>Mineral</td>
<td>11–90</td>
<td>20 vol%</td>
<td>≥36 mm (70°)</td>
<td>2–4</td>
<td>≥10</td>
</tr>
<tr>
<td>Chemloul et al. (2009)</td>
<td>Glass</td>
<td>270</td>
<td>2 vol%</td>
<td>≥0 mm (60°)</td>
<td>8</td>
<td>≥2</td>
</tr>
<tr>
<td>Hunter et al. (2011)</td>
<td>Glass</td>
<td>10</td>
<td>5 vol%</td>
<td>300 mm (90°)</td>
<td>1</td>
<td>≥15</td>
</tr>
<tr>
<td>Kotzé et al. (2013)</td>
<td>Kantal</td>
<td>N/A</td>
<td>17 vol%</td>
<td>≥16 mm (70°)</td>
<td>4</td>
<td>≥8</td>
</tr>
</tbody>
</table>

* Sedimenting particles.
* Pitch of 64 element transducer.

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Towards the Measurement of Local Particle Mass Fractions in Magnetite Suspensions

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Towards the Measurement of Local Particle Mass Fractions in Magnetite Suspensions

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Abstract—In the mining industry, magnetite particles are transported in suspensions with water through different stages of the process. In some of these stages, it is of interest to monitor both the concentration and particle velocity over a cross-section of the flow. High particle concentration makes development of flow measurement techniques challenging. An additional challenge is that the flow is often accessible from one side only, which further limits the selection of applicable techniques. Previous work by the authors focused on using pulse-echo ultrasound for flow velocity profile estimation. In this paper, the same setup is used to simultaneously study local variations in solids concentration.

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. We demonstrate how a short-time (windowed) Power Spectral Density (PSD) estimate can be used to obtain qualitative information about local solids concentration variations.

For demonstration, a magnetite suspension carrying up to 7.5 vol% particles (29 wt%, mean particle size 34 μm) is pumped through a closed rectangular channel. When the pump is stopped, pulse-echo ultrasound (with a center frequency of 2.25 or 3.5 MHz) is used to monitor the sedimentation process. Nine snapshots of the process are included. These show a time lapse of the sedimentation, with 5 s between each image. It is clear that the short-time PSD is a good indicator of local mass fraction variations.

I. INTRODUCTION

In the mining industry, magnetite particles are transported in suspensions with water through different stages of the process. In some of these stages, it is of interest to monitor both the concentration and particle velocity over a cross-section of the flow, e.g. to develop models for efficient control of the unit processes. To investigate methods suitable for this purpose an experimental platform has been built.

Previous work by the authors [1], [2] focused on using pulse-echo ultrasound for flow velocity profile measurements. When used for velocity measurements the pulse echo ultrasound method provided non-intrusive measurements, operation in opaque suspensions, and a fast sampling rate.

In 2002 Carlson and Martinsson [3] used a transmitter-receiver setup, where they compared measurements to single scattering theory. A linear dependency between the coefficient of excess attenuation and suspension solids concentration was found to hold for concentrations up to approx. 2.6 vol% solids. Hunter et al. [4] studied settling and movement of the settling interface (see Fig. 2). Studying homogeneous suspensions, they also found a linear decay on a dB scale of backscatter strength with suspension depth was found (40-160 mm from the transducer). Hunter et al. [5] compared experimental data to backscatter theory, this suggested that the single scattering theory is invalid for systems with particle concentrations greater than 0.1 vol%.

Wöckel et al. [6] used a narrow measurement cell, resembling what can be found e.g. in analytical instruments. Linear correlation was found between suspension solids concentration and the signal amplitude standard deviation. The measurement depth was e.g.: 16 mm in a suspension of 4.5 vol% solids and 5 mm in a suspension of 30 vol% solids. Weser et al. [7], [8] used the same setup as [6]. They studied how peak backscatter amplitude increase with mean particle size. Using a 6 MHz transducer good correlation was found for mean particle sizes between 10-54 μm, and using 10 and 14 MHz transducers good correlation was found for particle sizes of 7-23 μm.

In the current work, the equipment is used in a manner that made it possible to acquire information about local particle concentration and local particle velocity simultaneously, but focus is on solids concentration measurements only. One compact device (transducer) is used for both transmitting and receiving signals, which makes the method versatile. Focus is on the applicability to suspensions of high concentration of fine particles in water. The aim is to analyze the Power Spectral Density (PSD) of the backscattered signal to extract information about local solids concentration. The ultimate goal is to be able to estimate absolute local solids concentration.

II. EXPERIMENTAL SETUP

Magnetite suspensions with controlled solids concentrations are pumped through a closed rectangular channel. When the pump is stopped, pulse-echo ultrasound is used to monitor...
the settling process. Ultrasound pulses are transmitted into the suspension and the resulting backscatter is treated as random signals carrying information about the suspension. The statistics of the signal vary with solids concentration, particle size distribution, particle density, etc.

The experimental setup (Fig. 1) consists of a flow cell (50x75 mm) connected to the support equipment in closed loop made of rubber hosing with an internal diameter of 50 mm. The flow is driven by a progressing cavity pump (Netzsch NM053BY01L06B, www.netzsch.com) capable of creating a flow speed of up to 1 m/s in the flow cell. The pump motor is controlled with an AC drive (Emotron VFX48-010, www.emotron.com) and the suspension temperature is stabilized by a heat exchanger fed with cold tap water.

The measurements are made using two immersion transducers, Olympus V306, 2.25 MHz and V382, 3.5 MHz (www.olympus-ims.com). The transducers are placed at a 45° inclination at the end of the channel (to be able to make simultaneous velocity measurements, see \[2\]). The transducers are connected to a computer controlled pulser-receiver (Panametrics 5800PR, www.olympus-ims.com). Pulse timings are controlled by an Arduino Duemilanove running custom software. The received backscatter signal is processed by a digitizer (ADQ214, www.spdevices.com). Before each ultrasound measurement the suspension temperature in the mixer (M) is measured using a digital thermometer (ASL F250).

When the pump is stopped the suspension begins to settle, and a sediment bed begins to form on the bottom of the cell.

### III. Theory

In each measurement, the ultrasound transducer transmits a short pulse into the flow. The backscattered sound from the particles in the flow is then sampled using the digitizer and stored as the signal \( p[n] \), \( n = 0, 1, \ldots, N - 1 \). This signal, \( p[n] \), is random by nature, and due to attenuation and multiple scattering (in high concentration suspensions), the underlying random process can not be assumed to be stationary. This means that the signal characteristics will vary as a function of depth, local mass fractions, etc. For a short segment of \( p[n] \), however, we may assume stationarity, at least in a wide sense. So, let

\[
x_k [m] = p[k + m], \quad (1)
\]

where \( k \) is the position of the window, \( m = 0, 1, \ldots, M - 1 \), and the window length \( M \ll N \). In other words, \( x_k [m] \) is an \( M \) samples long segment of \( p[n] \), starting at sample \( k \). The autocorrelation sequence of \( x_k [m] \) is defined as

\[
r_{x_k} [l] = \mathbb{E} \left[ x_k [m + l] \cdot x_k^* [m] \right], \quad (2)
\]

where \( \cdot^* \) denotes complex conjugate and \( l \) is the lag. Assuming \( x_k [m] \) is real-valued and stationary, this can be estimated from the measurements as

\[
r_{x_k} [l] = \frac{1}{M} \sum_{m=0}^{M-1} x_k [m + l] \cdot x_k^* [m]. \quad (3)
\]

### Table I

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Transducer center freq</td>
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</tr>
<tr>
<td>Measurement time</td>
<td>( T )</td>
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</tr>
<tr>
<td>Pulsed repetition freq.</td>
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<tr>
<td>Sample frequency</td>
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<td>Sample bit-depth</td>
<td>( b_d )</td>
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</tr>
<tr>
<td>Window length</td>
<td>( M )</td>
<td>( 800 ) samples</td>
</tr>
</tbody>
</table>

Fig. 1. Experimental setup consisting of mixer (M), pump (P), heat exchanger (HE), flow cell (FC). Also sampling position (S) and data acquisition equipment; pulser-receiver (PR), digitizer (DAQ) and computer (PC), is shown.

Fig. 2. Sketch of suspension settling, dark color indicates high particle concentration. Before time 0 a turbulent flow of suspension goes through the flow cell. As the pump is decelerated to a stop the suspension starts to settle, and a sediment bed begins to form on the bottom of the cell.
The spectral contents, i.e. the PSD, of \( x_k[m] \) can be estimated as the periodogram of \( \hat{r}_{x_k}[l] \), which is the Fourier transform of \( \hat{r}_{x_k}[l] e^{-jl\omega} \), given by

\[
P_{x_k}(\omega) = \sum_{l=-M+1}^{M-1} \hat{r}_{x_k}[l] e^{-jl\omega},
\]

where the angular frequency \( \omega = 2\pi f \). In the figures in the following sections, the frequency axes is scaled so it represent the corresponding frequencies of the continuous-time signal \( x(t) \), i.e. in Hz.

Since attenuation and backscatter intensity can be assumed to depend on the mass fraction of particles, studying \( P_{x_k}(\omega) \) as a function of depth should give an indication of changes in local particle mass fractions. Hence, for each window position \( k \), we estimate the PSD as above.

### IV. Results

Nine snapshots of the settling process are shown in Fig. 3. Measurements are made in the concentration range of 0.24 to 7.5 vol% solids. The first snapshots, in the top images; a), d), and g), are taken just shortly after the pump begins to decelerate (at time \( t_0 \)). Then there is a time lapse (\( \Delta t = 5.0 \) s) between the images, showing the settling process, e.g: a), b), and c) for the 7.5 vol% solids case.

The transmitted ultrasound pulse, having a specified center frequency of 2.25 or 3.5 MHz, will naturally create a backscatter spectra with highest intensity around its center frequency. Low local solids concentration gives less backscattering, and a lower intensity. Interpreting this information it is possible to qualitatively follow local mass fraction variations, as function of depth and time.

An increase in backscattered intensity indicates an increase in solids concentration, e.g: when the transmitted pulse reaches the settling interface the locally increased solids concentration gives rise to a strong echo. If the settling suspension has become of high solids concentration the signal is strongly attenuated. In a wide solids concentration range it is possible to monitor the settling process.

Comparing Figs. b), e) and h), from the position of the dashed arrows, it can be seen that the settling velocity decreases with increasing solids concentration, as expected, due to hindered settling.

Comparing Figs. c), f), and i), the position of the settling interface after settling for 10 s varies between approximately 25 and 5 mm from the bottom of the cell. However, a transducer with lower center frequency is used in the 7.5 vol% solids case (to achieve sufficient measurement depth) which
will push the apparent position of the interface closer to the channel bottom.

In Fig. 4 the response when using a 2.25 and a 3.5 MHz transducer is compared. The difference is most evident in b) vs. e), where the apparent position of the settling interface differs approx. 5 mm. This is most likely because the pulses with lower frequency (from the 2.25 MHz transducer) are not attenuated as fast when the solids concentration starts to increase in the settling interface. Also the perceived sharpness of the interface is higher when using the 2.25 MHz transducer. Differences can to some extent be attributed to experimental error, since the images come from separate measurements.

V. DISCUSSION

Using this method it is possible to track the settling interface. Also estimating settling velocity and when the style of setting changes from free to hindered should be possible. As can be seen in Fig. 3 the settling interface is not sharp, but is a transition from low to high solids concentration over some distance. However, also the window length in signal processing will influence the perceived sharpness of the interface.

At this time, the method is not able to estimate the total solids concentration. Based on calibrated experiments, it might be possible to calibrate a regression model which can do this. Combining estimates of quantitative local solids concentration with particle velocity profiling, the total mass flow of particles through the system could be estimated and the flow patterns could be visualized.

When working with an acoustic backscatter system the received signal has been attenuated and scattered several times. Even assuming single scattering the pulse has been attenuated on the way to the interaction volume, an unknown portion of the energy has been lost through scattering, and then the backscattered pulse is attenuated further on the way back to the transducer. To estimate the local solids concentration based on only the backscattered signal is a challenge.

Information is only available as long as the signal is strong enough; if the flow region of interest is too deep, or the concentration too thick, the signal will be attenuated below the noise level. When this happens the signal no longer carry any useful information about the flow. The local signal attenuation depends not only on solids concentration, but if it can be assumed that all properties beside the solids concentration is constant in the flow, then it should be possible to estimate a relative local solids concentration.

VI. CONCLUSION

In this paper, it is shown that the PSD of the signal is significantly affected by the mass fraction solids. By implementing a short-time (windowed) PSD it is possible to study how the frequency content of the signal varies with depth through the suspension.

By using the described method it is possible to qualitatively follow variations in local particle concentrations, as a function of depth and time, for suspensions with a wide range of particle mass fractions. Here the method has been demonstrated successfully in a suspension flow with a depth of 50 mm, and solids concentrations between 0.24 vol% (1.2 wt%) and 7.5 vol% (29 wt%).

In a settling suspension it is possible to follow the settling interface. As expected, the settling velocity varies with particle concentration. The apparent position of the interface also depends on the frequency range of the transmitted pulse.

REFERENCES


Direct measurement of internal material flow in a bench scale wet low-intensity magnetic separator

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Direct measurement of internal material flow in a bench scale wet low-intensity magnetic separator

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A B S T R A C T

In this work an ultrasound-based measurement method is used for monitoring of suspension velocity and build-up of magnetic material inside a wet low-intensity magnetic separator, a process used e.g. in beneficiation of magnetic ores. Today the only available option is to monitor material transport between unit operations, i.e. flow rate, solids concentration, and particle size distribution of suspension flow in pipes are measured online using standard equipment.

An acoustic backscatter system is fitted to the tank of a separator, and used to monitor the internal flow. A method called ultrasound velocimetry is used to capture internal velocity profiles. Simultaneously the backscatter signal intensity is used to get indications about local solids concentration of the flow, and build-up of magnetic material. The methods are evaluated in realistic conditions, where the effect of varying factors relevant to machine performance is investigated. The included factors are: the slurry feed rate, the slurry solids concentration, the magnet assembly angle, and the drum rotational speed.

The presented method gives useful information about the internal material flow inside the separator. The velocity measurements capture the, sometimes complex, internal flow patterns, for example the presence and velocity of a recirculating flow in the dewatering zone. Additionally, keeping a balanced material leading to the concentrate dewatering zone is important to separator performance. Using the signal backscatter intensity it is possible to qualitatively monitor this material leading. Generally these direct measurements can aid in improvements to machine design, process optimization, and process control.

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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 factors of major importance are: throughput, amount of gangue in the concentrate, loss of magnetic material in 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 factors.

We used LIMS to separate ferromagnetic particles from non-magnetic particles. The particles are fed to the separators in suspension with water, and the material is separated into a thick magnetic concentrate and a dilute tailings stream. For a more detailed description see e.g. Stener (2012). Fig. 1 shows schematic drawings of separators with 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 Portes et al. (1988).

There are a large number of factors influencing magnetic separator performance. Dardis (1989) and Morgan and Bronkalla (1993) describe a number of these, for example, the feed rate of magnetic material, the magnetic grade of the feed, the feed solids concentration, the magnet assembly angle, and the drum rotational speed. In addition there are a number of machine design parameters which affect the separator performance, e.g. the drum-to-tank clearances, the separator magnet assembly design, and the separator tank design. Dardis (1989) worked with the process of dense medium
recovery, which has many similarities to the process of magnetic separation of fine magnetic in preparation for pelletizing.

Also Limto (1977) studied the factors affecting separation performance and found magnetic flocculation inside the separator to be the major mechanism for recovery of fine magnetic 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 Limto (1977) the factor which limi\textit{t} capacity when working with coarse 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 lay on counter-current type magnetic separators used for cleaning of a magnetic 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, which controls how high the magnetic material is lifted by the magnets and the drum in the concentrate dewatering zone; a high lift gives increased throughput and less material build-up in the dewatering zone.
- The drum rotational speed; a faster rotational speed gives more capacity for material throughput, but also less time for water to drain.
- The distance between the overflow weir and the separator drum; a wider gap gives an increased capacity for material throughput, but also a risk of a more dilute concentrate.

To get a better understanding of the internal material transport processes in wet LIMS internal measurements are needed. Until now no means exist for internal measurements in process equipment like the wet LIMS. In this work the possibilities to do measurements inside a wet LIMS using two ultrasound-based methods combined with an acoustic backscatterer system (ABS) is investigated.

The first method uses cross-correlation between ultrasound echoes to estimate particle velocity in flow of suspensions. Already in 1976 Deol et al. used cross-correlation of ultrasound echoes to measure blood flow velocity. In a review by Heim and O'Brien (1993) the development of cross-correlation based ultrasound velocity measurements are summarized. The use of ultrasound sensors in the process industry is later reviewed by Hauptmann et al. (2002).

Using the second method, information about the local solids concentration is extracted from the backscatterer signal amplitude. This has been described in detail by e.g. Hunter et al. (2011); they used a pulse-echo ultrasound based system to monitor particle
seeding rates, sediment bed formation, and bed compaction. These experiments were made in suspensions of 5 wt% glass beads. Hunter et al. (2012) was able to estimate solids concentration in homogeneous suspensions and monitor settling suspension (up to 10 wt% solids). Wöckel et al. (2012) also studied measurement of solids concentration they used a narrow measurement cell, resembling what can be found e.g. in analytical instruments. Using the standard deviation of the signal amplitude they were able to estimate the solids concentration of homogeneous suspension, e.g. in suspensions with up to 25 wt% solids, in a 5 mm passage.

The main purpose of this work is to study how the operational conditions of wet LIMS and similar equipment handling suspensions of high solids concentration, can be monitored 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 estimate of the thickness, and thickness variation, of the magnetic layer attached to the separator drum. This information would give us new possibilities to control, optimize, and develop the process of wet magnetic separation. The experiments are made in the context of wet LIMS utilized for separation of fine magnets 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.

2.1. Experimental setup

The wet LIMS used is a SABA laboratory unit (TU-307/2-16) of dimensions 600 x 115 mm filled with a purpose-built countercurrent (CCT) type tank, see Fig. 2(a). The characteristic dimensions are scaled 1% from a full size industrial separator (the Metro 65-200 mm counter-current type separator). The custom made separator tank consists of walls made from a white thermo-plastic, a front made from a transparent 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 separator are circulated back to the mixer, see Fig. 2(b). The flow is driven by a progressing cavity pump.

![Figure 2](image_url)

**Fig. 2.** Experimental setup. (a) Laboratory scale wet LIMS with purpose built tank, of counter-current type. 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: pulse o reviewer (PR), digitizer (DAQ), and computer (PC). Close up shows the four available sensor positions. In this study, positions 3 and 4 (with crossing path) are used.

pump (Metzsch N300/3B, www.metzsch.com) controlled by an AC drive (Emotron VX408-010, www.emotron.com). The suspension temperature is stabilized by a heat exchange fed with cold tap water. The parts are connected using rubber hose with an internal diameter of 50 mm. To keep the sensors free from settling particles a small water flow is introduced close to the transducers using a peristaltic pump (Watson-Marlow 503S, www.watson-marlow.com). This pump is stopped momentarily during all ultrasonic measurements.

2.2. Ultrasonic measurements

An acoustic backscatter system (ABS) is used in study the material separation, transport, and dewatering processes of the wet LMS described above. Two methods for signal processing are combined and evaluated in a realistic environment. The first method, ultrasonic velocity profiling (UVP), is a pulse-echo method using cross-correlation to estimate particle velocity; see e.g. Steiner et al. (2014a). Using this method it is possible to measure how particle flow velocity varies with distance from the transducer. The UVP method is also extended to estimate not only particle velocity in the direction of the transducer, but also particle velocity in arbitrary direction in a two-dimensional plane. This is accomplished by combining the measurements from two simultaneous UVP measurements.

Using the second method Steiner et al. (2014a) demonstrated that a short-time (windowed) Power Spectral Density estimate can be used to obtain qualitative information about local solids concentration variations. A variation of this method is used, and ultrasonic pulses are transmitted into the suspension, and the resulting backscatter is recorded. The amplitude of the backscatter signal depends mainly on the solids concentration, particle size distribution, and solids density of the suspension. If the same material is used throughout the experiment, the backscattered amplitude can give good indication about the local solids concentration.

2.3. 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. This centre frequency was selected to give a balance between signal strength and measurement depth, see e.g. Steiner et al. (2013a, 2013b). Each transducer is controlled by a pulse-receiver (Panametrics 5600PR and 5602PR, www.olympus-ims.com). The received backscatter signal is processed by a digitizer (ADQ214, www.spectev.com) featuring 400 MSp/s at 14 bit resolution. Pulse timings are controlled by a microcontroller (Arduino Duemilano, www.arduino.cc) running custom software. Before each ultrasonic measurement the suspension temperature in the mixer is measured using a digital thermometer (Agilent 3500, www.agilent.com).

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 60 µs, 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 2.5 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 of 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.

2.4. Signal processing

The local particle velocity in the direction of the transducer is calculated using UVP, the method is only summarized here; more details can be found in e.g. Steiner et al. (2014a). 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 particle 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 the particle velocity \( v_p \) in the direction of the transducer \( \mathbf{d}_l \):

\[
\mathbf{v}_p = \mu \mathbf{d}_l,
\]

(1)

The porosity of the measurements \( \mu \) are calculated using the known centre position of the face of the transducers \( \mathbf{q} \), the acquisition times \( \mathbf{t} \), and speed of sound in water \( c_{sw} \) at the measured temperature.
To calculate a 2D velocity vector, two simultaneous measurements are made using two transducers accessing the flow from two directions. Using the measurements from both transducers (V_{uax} and V_{Sam}) two planes are positioned in 3D-velocity space, as seen in Fig. 4. A plane is generated by assuming that the flow velocity perpendicular to both transducers (in the axial direction of the separator drum) is zero. The combined velocity (v) is calculated as the intersection between these three planes. For the presentation of the results, the measurement position is set in the middle plane between the two original measurement positions: \[ p = (p_{uax} + p_{sam})/2 \] (3)

The measurements from the two transducers are paired starting from the sample where the measurement paths intersect (see the close up in Fig. 2(b)).

2.5 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. The separator was illuminated by a 250 W floodlight. A frame rate of 40 fps at a resolution of 1280 x 1024 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.

2.6 Experimental design

The investigations are carried out as a designed experiment, a 2^{6-1} factorial design of four factors. The factors included are: the feed solids concentration, the feed rate, the drum rotational speed, and the magnetic assembly angle. Table 1. Additionally two centre points were selected, and each point was run three times to assess the repeatability of the method. With this experimental setup it was not feasible to vary the feed solids concentration independently. Neither was it possible to set a precise magnetic assembly angle in-between the low and the high angles. To still get some indication of the repeatability it was assessed separately for each of the two concentration levels. For the remaining factors the high magnetic assembly angle was used together with a drum rotational speed of 75% and a feed pump motor speed of 1600 rpm. Measured factor levels for all runs are included in Table 2.

The target feed solids concentration is achieved by mixing dry magnetite powder with water. The magnetite material (grade 65% Fe) used was supplied by the SKAB (www.skab.com) from the RA1 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 μm, and 85 wt% of the material is finer than 45 μm. The stated concentrations are estimated by sampling the stream, at (51 in Fig 3(b), 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 concentration was 4.5% (RSD = 1.3%) and for the high level it was 9.7% (RSD = 0.67%) by volume, corresponding to 15% and 35% by mass, respectively.

The target slurry feed rate (pump motor speed) is controlled by an AC drive via MATLAB. The same samples used for estimating the feed solids concentration above was also used for calculating actual slurry flow rate, by sampling the feed stream during a specific period of time. Table 3 shows the measured slurry flow rate together with calculated solids feed rate. The maximum feed rate of 20 kg/min corresponds to 1.2 tonnes/h, or (since the drum width is 115 mm) 10 tonnes/h/m drum length.

The target drum rotational speed is controlled by a mechanical lever on the driving motor, however the speed is also affected by the magnetic material leading in the separator. Therefore the rotational speed was calculated from the video footage of each experiment. On the few drum speed factor levels 100%, 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 an

<table>
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<th>Exp no</th>
<th>Drum speed (rpm)</th>
<th>Feed rate (t/m²h)</th>
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</table>

average 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 was adjusted between two fixed angles. The position of the magnetic pole closest to the concentrate discharge was determined using a steel blade, see Fig. 6. A change in magnetic assembly angle of 6° corresponds to 10 mm on the 2000 mm circumference. All experiments with their measured levels have been compiled in Table 2.

3. Results and discussion

Particle velocity measurements are made on the concentrate side of a laboratory scale wet LMS. Simultaneously the backscattered signal amplitude is used to get information about the loading of magnetic material in the separator. The ultrasound measurements are complemented with video footage through the transparent wall of the separator tank. Below the main effects of varying factors important to separator performance is described qualitatively.

In the two-dimensional particle velocity plots, e.g. Fig. 7 (a) and (b), the velocity is measured in the concentrate devolatizing zone, see also Fig. 2(b). Each measurement uses data from 512 profiles measured over a time-span of 2.56 s corresponding to a few drum rotations. The velocity is measured approximately at the centre of the separator drum, and the axial velocity is assumed to be zero. By using a third transducer it should be possible to make a third measurement with a component also in the axial direction, and thus being able to estimate the velocity in 3D. However, in this particular part of the separator the axial flow is likely to be smaller and less interesting. By only using two transducers the complexity of the system, signal processing, and data visualization is reduced. Also, it would have been a challenge to fit all three transducers in this small laboratory scale separator. If the current method were to be extended to 3D it would not affect the 2D-measurement. The 2D-velocity vector would be used together with the third measurement to estimate also the axial velocity.

The video footage, e.g. Fig. 8(e) and (f), covers approximately the same part of the separator tank as the velocity measurements. But, since the video recordings only capture the material flow and build-up just inside one of the tank walls, the recordings are probably affected by wall effects. However, in this narrow separator, where the slurry feed is evenly distributed over the full width of the tank, the wall effects appear to be small and the videos give good indications about the internal flow and material build-up. In a full scale separator, on the other hand, the same video recording method would probably not work as well. This, since the full scale separators have wide drums (up to 3.6 m, Meeton 2014) and the slurry feed is more centred towards the middle of the drum.

By studying the backscattered signal amplitude, e.g. Fig. 8(e) and (f), it is possible to get qualitative information about build-up of magnetic material inside the separator. The backscatter strength is shown for varying distance from the tank bottom, and time. The distance from tank bottom is defined in the direction of the drums; 30 mm corresponds to the approximate position of the rotating drum surface. By monitoring the flow during a few seconds it is possible to see if the build-up is stable, or if it varies with time. These results use the same raw data as the velocity measurements above, so the measurements are made in the same location in the separator (see Fig. 2(b)). When the transmitted ultrasound pulse reaches the build-up of magnetic material on the separator drum the backscattered amplitude increases temporarily, due to the increased acoustic impedance of the suspension. But due to the high signal attenuation in the magnetic build-up the signal is also attenuated fast. When the feed rate of solids material to the separator is low, and the
build-up of magnetic material is low, the backscattered signal amplitude looks typically like in Fig. 6(a); the signal is attenuated gradually as it travels through the suspension. Another case is shown in Fig. 6(c), where more than half of the measurement zone is packed with magnetite. Due to this, the magnet build-up is lower than in Fig. 6(b). A strong backscattered signal is observed at around 12 mm from the tank bottom. After passing this point, the signal strongly attenuates and is not detectable at the signal is almost extinct.

3.1. Effect of varying the magnet assembly angle

At normal separator feed levels, the position of the magnet assembly affects the position of the magnetic build-up in the concentrate dewatering zone. A higher angle means that the magnet is closer to the media, which reduces the distance in the dewatering zone. In the experiments, see Fig. 7(a), this can be seen as an undisturbed downward flow. If the magnet material is clean, as in this case (95% magnetite), then the return flow is low and the magnet build-up is not significant. The particles contain mostly non-magnetic gangue. At a lower magnet angle, there is less space in the dewatering zone, and the flow is still developing in the measurement zone, see Fig. 7(b). The higher lift of the magnetic build-up can also be seen in the video footage in Fig. 7(c) and (d).

3.2. Effect of varying the drum speed

Using a high drum speed increases the separator capacity to remove magnetic material from the dewatering zone, but it is also likely to bring more water (and fine gangue) to the concentrate. A high drum speed, see Fig. 8(a), has a similar effect on the flow profile as a high magnet assembly angle, since both settings help in extracting magnetic material from the concentrate dewatering zone. At the lower drum speed level, see Fig. 8(b), there is more material build-up in the dewatering zone, and the flow is still developing in the measurement zone. This material build-up is more evident from the backscatter amplitude in Fig. 8(c). However, the difference between the two photographs (Fig. 8(c) and (d)) is small compared to the difference between the backscatter amplitude plots (Fig. 8(c) and (d)). This is probably due to wall effects; in this case, the material build-up is built up by the wall difference between the two photographs (Fig. 8(c) and (d)).

3.3. Effect of varying the feed solids concentration

On the high level of feed solids concentration, the feed of magnetic material is so high that it results in strong material build-up, and overload in the dewatering zone. This build-up prevents suspension flow in the dewatering zone. Additionally, due to the very
high solids concentration (30-40 vol%) in the magnetic build-up, the ultrasound measurement method is not able to reliably measure the particle velocity. However, some profile is always generated. For example, the profile measured for the high feed rate case in Fig. 5(a) is not realistic. In the backscatter amplitude plot in Fig. 5(e), it is shown that the signal strength is low in most of the measurement zone, compared to Fig. 5(f). The strong material build-up is also confirmed by the video footage in Fig. 5(g).

The highest solids feed rate levels (high feed solids concentration together with high slurry feed rate) was actually chosen to mimic material overload conditions in the separator. This was achieved, and the video footage show strong material build-up for all combinations where feed solids concentration and slurry feed rate are set at their high levels. The maximum level of solids feed rate (20 kg/min = 10 tonne/h/m drum) is actually comparable to the typical feed rate to a 1500 mm separator (11 tonnes/h/m drum; Sundberg, 1998).

3.4. Repeatability

To assess the repeatability of the method, the same combination of factor levels was run three times (in the beginning, in the middle, and in the end) for both levels of feed solids concentration. Fig. 10 shows that the velocity measurements have sufficient repeatability. Also, the velocity profiles from the high level of solids feed rate are more consistent and less noisy compared to the low level of solids feed rate.
concentration and the backscatter amplitude plots show similar level of repeatability.

4. Conclusions

Using the described ABS it is possible to monitor important flow properties inside a wet LIMS. During normal operation it is possible to estimate flow velocity with sufficient precision. The velocity measurements capture the sometimes complex internal flow patterns of the separator, for example the presence and velocity of the recirculating flow in the dewatering zone can be measured.

It is also possible to get qualitative information about material build-up inside the separator using the backscatter signal amplitude. E.g. keeping a balanced material loading in the concentrate 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. Using the described method it is possible to monitor this material loading.

From a more general view the described ABS could be used to monitor flow of opaque suspensions in narrow channels in various processes.
applications. When applied to flows of mineral suspensions with high solid concentration, similar to those in wet LIMS, the method 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 the future the performance of these methods in larger magnetic separators, pilot or full scale, should also be evaluated. 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, or investigate if there are differences along the width of the drum. Apart from the wet LIMS these methods could also be used in other applications where opaque suspension flow in narrow channels, e.g. hydrocyclones, inclined plate separators, and thickeners. The measurements could be used to gain a deeper understanding of the process, in process control, or for validation of simulations.

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References


Fig. 16 The same experiment repeated three times, indicating good repeatability. Levels used in this case are low feed solids concentration, medium feed rate, high magnet assembly angle, and medium drum speed.


A Stokesian dynamics approach for simulation of magnetic particle suspensions

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A Stokesian dynamics approach for simulation of magnetic particle suspensions

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A B S T R A C T
The dynamic behavior of micron scale ferromagnetic particles in suspension is of interest for various mineral beneficiation processes. It is, however, difficult to experimentally study such processes at the particle level. In these instances it can be advantageous to resort to suitable simulation methods.

Stokesian dynamics is a mesh-free numerical technique developed for suspensions of non to mm size particles. The method inherently considers hydrodynamic interactions, but additional interaction models can be included depending on the system under investigation. We here present a Stokesian dynamics (SD) implementation, which allows for simulation of the motion of suspended magnetic particles in presence of an external magnetic field. The magnetic interaction model includes particle field interactions as well as pairwise interactions between magnetic particles.

Simulations are compared with experiments using a laboratory-scale flow cell. The method is shown to be realistic for studying ferromagnetic suspensions in mineral processing applications, and can be used in understanding and predicting the efficiency of mineral separation processes. © 2015 Elsevier Ltd. All rights reserved.

1. Introduction

The study of magnetic particle suspensions is relevant for better understanding of wet-state separation processes in mineral processing and recycling (Jensen et al., 2014; Møller et al., 2014; Sverdlov and Park, 2003) as well as various other applications or processes based on magnetic properties of particles for instance magnetorheology, micro-robots, and medical applications (Costa and Costa Branco, 2009; Lu et al., 2016; Roestiger et al., 2005; Lamm et al., 2017).

Numerical simulation of magnetic particles in suspension have been conducted within a number of probabilistic and deterministic particle dynamics simulation disciplines, including Monte-Carlo simulation (Saitoh et al., 1999; Saitoh, 2006), lattice-Boltzmann-discrete element method (LB-DEM) (Yuan et al., 2010a,b); lattice-Boltzmann-Brownian dynamics, LB-BD (Saitoh, 2012) and Stokesian dynamics (Saitoh et al., 1998; Saitoh, 2002; Irinia and Yokomine, 2007). The focus of these studies have not been directed specifically towards mineral separation processes, but have rather been phenomenologically oriented or related to novel uses of magnetic effects in applications for instance within nanotechnology, ferrofluids, and drug delivery systems. One of the more accurate methods related to evaluating the combined effect of liquid phase flow and magnetic effects is the LB-LES-DEM approach (Lattice-Boltzmann-large Eddy Simulation-Discrete Element Method). Work in this direction has been described by Han et al. (2007, 2010a,b). The method is, however, restricted to a very limited number of particles due to the high computational expense.

Some relatively recent studies have been carried out utilizing combined DEM-FEM-CFD (Discrete Element Method-Finite Element Method-Computational Fluid Dynamics) simulation approaches for simulating high-gradient magnetic separation (HgMS) and wet low-intensity magnetic separation (LIMS). Such work has been published by Limmer et al. (2013) and Muraru (2013). These types of coupled methods are beneficial in offering one or sometimes two-way coupling between continuum and discrete simulation disciplines by using commercially available simulation tools. The drawbacks mainly come from inherent limitations of each individual method or the coupling between the methods. This can be exemplified by the typical one-way hydrodynamics coupling or otherwise simplified description of the interparticle hydrodynamics, limited possibilities to describe free surface interactions, etc. Although enabling the simulation of fairly large systems and allowing a relatively accurate representation of the macroscopic magnetic field, these methods are not able to fully...
account for the complex mechanisms that can arise as result of combined effects of magnetic, hydrodynamic and possibly other relevant particle-level interactions.

In processes such as wet magnetic separation, single particle properties and interactions play a key role. It is therefore strongly motivated to build such work on predominantly particle-oriented simulation approaches where particles can be individually designated relevant properties and various mechanisms can be reliably studied at the particle level. A benefit of the Stokesian dynamics technique is that it is developed for particles in suspensions and thus allows for study of high-concentration suspension behaviour without need for the computationally more costly DEM-CFD or DEM-FEM coupling, or less accurate tracer particle simulations by using continuum-type approaches. The Stokesian dynamics technique allows relatively straightforward addition of force models describing various types of particle interactions in liquid media (Tovakkoli et al., 1997; Nepola, 2004).

In this paper we propose a Stokesian dynamics-based simulation framework which can combine the accuracy of suspension-oriented particle methods with the efficiency of a simplified mesh-free mathematical approximation of the magnetic field and fluid flow. The model is illustrated and qualitatively evaluated in the context of a number of simulation examples. Furthermore, simulations are compared with experimental results using a laboratory-scale flow cell. We also discuss the wider applicability to the model for numerical simulation-based evaluation of magnetic separation efficiency.

2. Method

2.1. Stokesian dynamics

The Stokesian dynamics technique was originally developed in the 1980’s for the study of many-body interactions in nonequilibrium suspensions (Bear and Brady, 1984; Brady and Bear, 1988; Brady, 2003). Due to the possibility to include additional interaction models, efforts have since then been made to enable consideration of various phenomena, e.g., colloidal interactions, Brownian motion, and interparticle effects from added dispersed phases (Tovakkoli et al., 1997; Nepola, et al., 2004; Sand, et al., 2009). There has also been much work devoted to increasing the computational efficiency of the technique (e.g., Bird et al., 1996; Squires and Brady, 2001).

Earlier approaches using the Stokesian dynamics technique for studying ferromagnetic particle suspensions have included the definition of the external magnetic field as a homogeneous field covering the full simulation domain, as well as describing particles as being identical and of monodisperse size distributions (Satoh et al., 1998; Insa and Yokomine, 2007). However, there have also been made to increase the computational costs by introduction of a chaseterized simulation approach (Sand, 2002).

Stokesian dynamics simulations are based on the N-body coupled Langevin equation (Bear and Brady, 1988) which is a variant of Newton’s second law of motion can be written in the form

\[ \frac{du}{dt} = \vec{F}_{\text{m}} - \vec{F}_{\text{d}}' + \vec{F}_{\text{f}}. \]  

(1)

Where \( u \) is the change in velocity, \( \vec{F}_{\text{m}} \) is a function of the various forces influencing the particles. These forces are commonly divided into three types. Hydrodynamic forces, \( \vec{F}_{\text{d}}' \), includes a drag force resulting from the macroscopic flow of liquid, pairwise interaction forces between particles or between particles and boundaries mediated through the interstitial liquid. Interparticle forces, \( \vec{F}_{\text{f}} \), can include e.g., colloidal or steric forces between particles, but also in the case of magnetic properties forces which arise between magnetized particles. Single particle forces, \( \vec{F}_{\text{m}} \), result from various macroscopic forces that influence the motion of particles. This can for instance include Brownian forces that result from thermal vibration of small particles. In this work, the attraction of magnetic particles to an external stationary magnetic is considered as a single particle force. The magnetic interaction models specific to this work are discussed in Section 2.2. All other models are presented and discussed in detail elsewhere (Tovakkoli et al., 1997; Nepola, 2004; Sand, et al., 2009).

Due to the additivity of forces in this expression, interactions beyond the typical hydrodynamics and particle interaction models can be included in a relatively straightforward manner. For reducing the computational expense, it is often necessary to conduct an analysis of governing forces through the simulation of a number of dimensional numbers. This analysis includes a relative comparison between different forces in order to determine their relative significance. In Stokesian dynamics, the most important non-dimensional number is the particle Reynolds number, \( R_p \). This describes the relative importance of inertial versus viscous effects as

\[ R_p = \frac{\rho_{\text{p}} v_{\text{p}}^2 d_{\text{p}}}{\mu} \]  

(2)

where \( \rho_{\text{p}} \) and \( v_{\text{p}} \) are the density and viscosity of the liquid medium, respectively. \( \mu \) the characteristic particle size and \( \mu_d \) the viscosity of particles relative to the liquid. If the particle Reynolds number is small, defined as \( R_p < 1 \), it can be assumed that viscous effects dominate and particles can be expected to react instantaneously to forces influencing them. This approximation is relevant for small particles that are freely moving with the fluid, and thus suitable for suspension flow simulations. For instance a jam particle moving at a velocity of 0.1 m/s relative to the liquid phase (water) has a particle Reynolds number of 10.

While this form of numerical analysis is relatively straightforward for many-body simulations, it becomes complicated in systems with rapidly changing conditions or where conditions vary considerably at different locations of the domain. This can for instance be assumed to be the case near the magnetic source in the simulations presented in this work, as in this region magnetic interaction forces will dominate.

The Stokesian dynamics approach utilized in this work includes adaptations to the general model expressions by fitting them to data from CFD simulations. This extensive process is described by Sand et al. (2009) and Nepola (2004). Compared to the standard Stokesian dynamics approach, the modifications significantly improve the accuracy of simulations when studying suspensions of wide particle size distributions and systems where particles are in close contact. This extends the maximum 11/0 size ratio between particles, which is traditionally considered as a limitation in Stokesian dynamics (Kim and Karrila, 1991).

2.2. Magnetic interactions

In this work, we aim at creating a flexible implementation for simulation of ferromagnetic particle suspensions under influence of three-dimensional magnetic fields with an arbitrarily assigned magnetic source. This is advancing the previous state-of-the-art in Stokesian dynamics simulations, where suspension behaviours have been studied in simplified, homogeneous magnetic fields (Satoh et al., 1996; Sand, 2002; Insa and Yokomine, 2007).

Particle motion and interactions related to magnetic forces are in this work based on three force models. These include interaction between the particles and a stationary magnetic point source, interparticle magnetization and orientation of magnetic particle clusters along the magnetic field. There are a number of assumptions made in order to increase the computational efficiency.
Particle magnetization is assumed to be homogeneous, and vary depending on the local magnetic field, which is a function of the distance to the magnetic source point. The magnetic source is furthermore viewed as an infinitely long dipole. 

- Particles are assumed to always be oriented in the direction of the magnetic field, as defined by the position of the magnetic point source. Consequently, particles are not specifically described as magnetic dipoles. Their magnetic dipole orientation is therefore always known and calculation of magnetic torque on individual particles can be omitted. Since sphere-like particles in suspension have a small rotational drag this is deemed a reasonable approximation.

- Particles which are defined as being in close contact with each other in the vicinity of the magnetic pole are considered as being part of a magnetic cluster, whereby an additional force model works to orientate the particle cluster with the magnetic field. This can be considered as a cluster-based torque model, which applies for particle pairs but not for individual particles.

- No back-coupling is assumed between magnetic particles and the macroscopic magnetic field i.e. magnetised particles do not explicitly affect this field. The localised effect that these particles have on the field is instead considered through the inter-particle magnetic interaction and cluster orientation models.

The relationship between magnetic susceptibility $\chi$, the intensity of magnetisation $M$, and the applied magnetic field $H$, for various materials is discussed by Wills and Napier-Munn (2006). While the volume magnetic susceptibility of paramagnetic and diamagnetic materials is nearly a constant, the relation between $M$ and $H$ for ferromagnetic materials is more complex. Modelling of magnetization curves has previously been attempted (Abrahamz, 1995), but due to the relative complexity of these expressions a simplified description was estimated for use in this work. In order to produce a realistic magnetization behaviour of ferromagnetic particles, it was therefore assumed that the intensity of magnetisation of a single particle, $M$, is a function of the magnetization, $M_s$, a magnetisation gradient, $g$, and ambient magnetic field $H$ according to

$$M = M_s e^{-gH}. \tag{3}$$

Particle magnetisation based on their distance from the magnetic point source is assumed to follow this expression. As can be seen this does not include any memory function for the magnetisation of particles. A comparison between the magnetisation model and experimental data is made in Fig. 1. The magnetisation intensity and applied magnetic field ($\mu$) can be expressed in SI-units (A/m) by dividing with $4\pi \times 10^{-7} \text{A m}^{-1}$.

The single particle attraction force towards the magnetic pole can be described by the expression

$$F_p = \mu_0 V_a M H $$ \tag{4}

where $\mu_0$ is the magnetic permeability of free space, $V_a$ a parameter that represents the magnetic volume of the particle, $M$ particle magnetization as discussed above and $V$ the magnetic field gradient (Murazaki 2013). In this work, the magnetic volume of the particle is calculated as the particle volume multiplied by a scaling factor which can be used to describe varying amounts of demagnetisation in particles. Due to the assumptions of a simplified magnetic field as discussed above, the magnetic field gradient is approximated in scale by a factor $1/2$, where $r$ is the separation distance between the particle and the magnetic source.

The magnetic dipole-dipole interaction force between two nearby particles can be defined as

$$F = \frac{2\mu_0}{4\pi} \left( \mathbf{m}_1 \times \mathbf{m}_2 \right) \cdot \mathbf{r} - 2f(\mathbf{m}_1, \mathbf{m}_2)$$ \tag{5}

where $r$ is the distance between the two magnetic dipole moments $\mathbf{m}_1$ and $\mathbf{m}_2$ the unit vector pointing from $\mathbf{m}_1$ to $\mathbf{m}_2$ (Yang et al. 1998). The implementation of the model is simplified by assuming that the particles are always oriented in direction of the external magnetic field. The relative (non-dimensional) magnitude and direction of the force between two magnetically interacting particles in a homogeneous magnetic field is illustrated shown in Fig. 2.

2.3. Algorithmic techniques

Various algorithmic techniques are typically incorporated in Stokesian dynamics codes in order to improve the computational efficiency of simulations. The implementations used in this work include a sparse matrix solver as well as a neighbour list technique which allows the calculation of only pairwise interactions of nearby particles. This significantly reduces the computational efforts (Swalla 1997, Sand et al. 2009). However, long-range interactions originating from the macroscopic magnetic field is not compatible with the neighbour list approach. In the algorithmic implementation the attraction of particles to the magnetic source is instead considered as a single particle force. Interparticle forces resulting from magnetisation and particle cluster orientation are still taken into consideration within the neighbour list approach. This allows for the calculation of long-range magnetic attraction forces simultaneously as the numerical implementation for particle-level interactions remains relatively efficient.

3. Simulation setup

The simulation examples presented in this work were constructed to allow comparison and later possibly validation against a laboratory scale flow cell, which can be equipped with an ultrasound transducer and magnets. The dimensions of the flow cell are $50 \times 75 \text{mm}$ (depth and width, respectively) and the length is $1 \text{m}$. Fifty mm is a typical distance between the magnetic drum and the tank bottom in a wet low intensity Magnetic Separator (LIMS), while $75 \text{mm}$ is wide enough to avoid unwanted interaction between the ultrasound signal and the side walls. The ultrasound transducer enables the tracking of flow velocity profile and localized solids concentrations in the suspension. If equipped with magnetic, magnetic material can be captured at the top wall of the flow cell. This allows the monitoring of magnetic material build-up near the magnet. During build-up it is possible to study, for instance, rate of build-up, or cake thickness as function of flow.
rate and magnetic field strength. Experimentally tested suspensions within this flow cell have included magnetic particles, $\mu_B = 34 \, \mu m$, at a concentration of 5–10 vol% and at a suspension flow rate of up to 1 m/s (Siebert et al., 2014). The flow cell setup is schematically shown in Fig. 3.

The simulation examples given below are designed to roughly correspond to the setup of the described flow cell. A pressure-driven (parabolic) flow profile is used to describe the flow of the suspension. Particles are randomly placed in the simulation domain at the start of the simulation. Due to the large number of particles (billions per cm$^2$) in the flow cell, a full representation of the particle system within the domain is not possible with current computational resources. Instead, the simulations below should be considered indicative of particle behaviour within the domain. In case a relatively complete picture is sought for only a small volume of the cell (typically less than 0.1 mm$^3$) can be considered. Only monodisperse systems of spherical particles are considered in the current simulations, with particle sizes of 2–5 μm. The Stokesian dynamics approach presented in this work can, however, also be utilized for simulation of particle size distributions.

4. Results and discussion

The above-described simulation approach is evaluated in a number of test cases to demonstrate the functionality of the constituent models and how they interact. The run time of a 2000 particle simulation using the method presented in this work corresponds to approximately 2 weeks on a 3 GHz single core processor. Results are visualized using the in-house developed software P3D++, based on the OpenCl platform (Sand, 2019).

Tracking of particle motions can aid in the understanding of capture criteria and near-magnet flow patterns based on the combined effect of hydrodynamics, magnetic, and other relevant forces. An example of such a simulation is shown in Fig. 4. Particles have at the start of the simulation been randomly placed in the simulation domain and a parabolic flow profile applied. It can be seen that particles close to the defined magnetic point source are able to migrate against the flow direction towards the magnet. If the distance to the magnet source is too long, particles attracted to it might not be able to reach it before being carried away by the flow. This is especially noted if particles need to pass the high fluid velocity region in the center of the flow channel.

It is known that non-magnetic particles in some cases can be captured within magnetic particle clusters and consequently carried with the concentrate (García-Martínez et al., 2013). The mechanisms of such non-magnetic particle entrainment is not known in detail, but can be studied by numerical simulation, for instance by investigating the interaction between macroscopic suspension flow, interparticle hydrodynamic effects, and magnetic forces. Stokesian dynamics is a highly suitable technique in this respect as it includes full representation of hydrodynamic particle interactions through the liquid medium, while typical approaches based on CFD-DEM or FEM-DEM assume that particles move along the liquid flow lines (Mutahar, 2013) but do not interact hydrodynamically with each other. This is especially relevant in high-concentration suspensions, where the calculation of hydrodynamic interactions in Stokesian dynamics strongly contributes to increased simulation accuracy (Nepali, 2004). It also needs to be noted, however, that neither this approach nor the CFD-DEM or FEM-DEM work discussed above include two-way coupling between the liquid phase and particles.

Another simulation was carried out with a suspension of 1000 magnetic and an equal number of non-magnetic particles. Fig. 5. Two distinct mechanisms that could result in particle entrainment were observed. The first being non-magnetic particles getting dragged or pushed by hydrodynamic or mechanical interactions with magnetic particles translating towards the magnetic source. The second mechanism was the flow of non-magnetic particles towards the formed magnetic cake by simple hydrodynamic drag by the flowing liquid medium. When suspended magnetic particles approach from behind and lock into the magnetic particle cluster, they may completely surround the non-magnetic particle before it has the chance to escape.


Fig. 2: Direction (left) and relative force magnitude (right) of interaction between two magnetised particles in an ambient magnetic field (R).

Fig. 3: Experimental flow cell setup, including mixer (M), pump (P), heat exchanger (HE) and flow cell (FC). The flow cell can be equipped with an ultrasound transducer as well as magnets at the same position (Siebert et al., 2014).

Fig. 4: Magnetic particles and their trajectories near a magnetic pole. The straight white lines mark the inner corners of the flow cell.

Fig. 5: Magnetic particles suspended in a fluid. Two distinct mechanisms that could result in particle entrainment were observed. The first being non-magnetic particles getting dragged or pushed by hydrodynamic or mechanical interactions with magnetic particles translating towards the magnetic source. The second mechanism was the flow of non-magnetic particles towards the formed magnetic cake by simple hydrodynamic drag by the flowing liquid medium.
In addition to particle entrainment, the simulation also shows the formation of chains of magnetic particles, which orientate in the direction of the flow. This is a result of particle magnetization and, consequently, attraction of particles to each other in the vicinity of the magnetic pole. The chains preferentially form in the low flow rate region close to the wall of the flow cell where magnetic forces dominate over viscous forces. Due to the pressure-driven (parabolic) flow profile, the flow rate at the centre of the cell is too high to allow formation of stable chains of magnetic particles. Strings of magnetic particles appear under some conditions to be able to eventually detach from the structure as seen in subfigures E and F.

As the number of particles in these simulations is relatively low, an alternative type of visualisation can be used. Instead of visualising individual particles, sticks were used to illustrate particles in close contact to each other. The position of sticks can then in turn be viewed as a high concentration region of particles or as an indication of particle aggregation due to magnetic or other forces. Such an example is shown in Fig. 6. The structure arising in simulations can be compared with the visually observable magnetic cake in an experiment using the flow cell shown in Fig. 3. Results appear very similar in terms of magnetic cake structure, with a strong build-up near the magnetic and a call of particles in the direction of the flow. It needs to be pointed out that since only particle clusters are illustrated in this example, individual particles that are not considered as forming part of a cluster are not shown using this mode of visualisation.

By adjusting the threshold distance at which particle contacts are filtered out, it is possible to adapt the visualisation to illustrate individual clusters of magnetic particles in close contact rather than the general increase in solids concentration shown in the previous example. An example of this is given in Fig. 7, where contacts between individual particles are shown as sticks with increased thickness at the interparticle gap. This gap can in practice be determined by a specified particle surface roughness parameter. The particle chains are formed as a result of the interparticle magnetisation, the particle cluster orientation model which adapts to the field lines extending from the magnetic pole and various hydrodynamic interactions.

The five examples discussed above illustrate numerical results along with a number of visualisation cases that can be produced using the method developed in this work. The simulation outcomes are reasonable in comparison with previous simulation work, experimental results and theory discussed in the introduction and method. Solids concentrations up to 3 vol% were successfully simulated, which is comparable to the maximum slurry concentrations used in the flow cell and also similar to the conditions in a real IUMS. Consequently, Stokesian dynamics appears to be a suitable method for simulation of magnetic phenomena in suspensions. With further development, the method is expected to allow relatively comprehensive studies to be carried out, e.g., related to mechanisms and interactions in magnetic separations. This could for instance include the effects of changes in material throughput, solids concentration and magnetic field strength on the selectivity of magnetic separation processes.

5. Concluding remarks

In this work, we have adapted a model for magnetic interactions to a Stokesian Dynamics simulation framework. This gives the capability to study the three-dimensional behaviour of ferromagnetic particle suspensions of varying particle size distributions subject to a magnetic field. The presented method builds upon previously conducted modelling and simulation work related to magnetic interactions in suspensions. The main advantages include the utilisation of improved model descriptions of particle hydrodynamic interactions, expansion of particle models beyond monodisperse systems and a flexible representation of the magnetic field. In earlier work, simplifications within these aspects carried risks of restricting the predictive value of simulations, especially with relation to particle interaction mechanisms resulting from the
combination of magnetic and hydrodynamic forces. This strongly motivates the use of a Stokesian dynamics approach and the modifications suggested in this work, which bears the primary benefit of offering more accurate hydrodynamic representation of polystyrene particle size distributions (Sand et al., 2015). A comparison between the approach discussed in this paper and work by other groups is made in Table 1. The model allows for systematic study of various mechanisms or properties related to ferromagnetic suspensions which, in turn, can have an influence on efficiency or selectivity of mineral separation processes. This can for instance include tracking of particle motion, study of the microstructure of the magnetic particle matrix and capturing mechanisms of non-magnetic particles. Examples presented in this work should, however, not be considered as a validation of the models, but rather a demonstration that reasonable results can be obtained. Due to the difference in particle system size and volume represented, simulations are not ideally corresponding to the flow cell setup and any study of differences or similarities between the two systems should therefore be restricted to qualitative comparisons. Given the considerations above, the examples demonstrated in this work is thus to be considered as giving indications of model capabilities rather than...
quantitative information on mechanisms or events taking place in the flow cell or in real magnetic separators.

As part of future development, the method should be adapted for studying mixed grain type particles. At the moment only binary systems of comparable magnetic properties are considered. In processes where single particle properties play a role, for example liberation of magnetic material from gangue and magnetic grade effects in magnetic separation, it is crucial to be able to define individual particle properties in the models. Further work should include the development of interaction models where the size of the magnetic domain could be varied for instance based on particle size. A long term possibility could be also implement size distributions of the magnetic domain for different particle size classes or by assignment of magnetic properties to individual particles by random procedures.

So far, the work has been qualitatively compared with flow cell experiments (Sener et al. 2014). Further systematic comparison or validation type tests could include more detailed comparison of particle solid concentration or structure near the location of the external magnetic. This would allow evaluation of the implemented model and possibly also adjustments of models or model parameters in order to produce a more accurate behaviour. Another possibility could be to quantitatively study non-magnetic particle capturing within the matrix of magnetic particles. This would however require a possibility to extract the magnetic cake from the flow cell and analyze the fraction of non-magnetic particles within.

Acknowledgements

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References


Paper VI

In-Situ Monitoring of Particle Velocities and Solids Concentration Variations in wet Low-Intensity Magnetic Separators

Johan E. Carlson, Jan F. Stener, Anders Sand, and Bertil I. Pålsson

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In-Situ Monitoring of Particle Velocities and Solids Concentration Variations in wet Low-Intensity Magnetic Separators

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Abstract—In previous work, we have shown how an ultrasound pulse-echo setup can be used to simultaneously measure particle velocity profiles and local solids concentration variations in solid/liquid particle suspensions. In this paper, we demonstrate a real-world case where the system is installed in a wet low-intensity magnetic separator, a process in which magnetic material is separated from gangue. The method was evaluated at LKAB’s R&D facilities in Malmberget, Sweden, on one of their pilot scale separators. The results show that it is possible to detect changes in the flow velocity patterns and the local solids concentration, as the operational conditions of the separator are varied.

I. INTRODUCTION

In the mining industry, which is a highly automated process industry, mineral material is transported between, and inside, various equipment to grind and separate the material into the desired fractions. This transport is done both in dry state and in suspension with water. With time the demands on the different processes increase, both because the simple ores are already mined, and also because of more restrictive environmental regulations. This gradual change calls for more precise methods in process monitoring and control.

In this paper the possibilities for using pulse-echo ultrasound for monitoring complex-geometry flow of high density mineral suspensions are investigated. A windowed cross-correlation based method is used for localized particle velocity measurements in two dimensions, and the Power Spectral Density is studied to extract information about local particle concentration. It is also shown how these methods can be combined and used in standard process equipment. The context selected for evaluation of these methods is a process common in mineral processing: wet Low-Intensity Magnetic Separation (LIMS).

II. THEORY

A. Ultrasonic Velocity Profiling

The method used for particle velocity measurements is called Ultrasonic Velocity Profiling (UVP). In each measurement, the ultrasound transducer transmits a short pulse into the flow. The backscattered sound from the particles in the suspension is then sampled at a sampling rate $T_s = 1/f_s$ and stored as the signal

$$p[n] = p(nT_s), n = 0, 1, \ldots, N - 1, i = 1, 2.$$ (1)

The two signals are acquired at a pulse-repetition frequency (PRF) so that the time between the two acquisitions is $T_{PRF} = 1/PRF$. If the PRF is high enough, we can assume that the particles in the interaction volume has moved like an entity, so that the backscatter signatures differ only by a time delay, $\tau_0$, proportional to the movement of the suspension during the time $T_{PRF}$. Finding this time delay can be done by a simple cross correlation of the two echoes, as

$$n_0[k] = \arg\max_m XC[m, k]$$ (2)

i.e. the time delay between the echoes is found at the lag $n_0[k]$ between the echoes that maximizes the cross-correlation between them. Since the particle velocity varies throughout the flow this time delay will depend on the depth through the flow; displacement of the flow has to be considered a function of depth. We therefore compute the cross-correlation between short segments of $p_1[n]$ and $p_2[n]$, thus resulting in one time delay estimate for each such pair of segments. In other words, let

$$x_1[k] = \{p_1[1 + k], p_1[2 + k], \ldots, p_1[M + k]\}$$

$$x_2[k] = \{p_2[1 + k], p_2[2 + k], \ldots, p_2[M + k]\}$$ (3)

be an $M$ sample long window from $p_1[n]$ and $p_2[n]$, respectively, and let $k = 0, 1, \ldots, N - M - 1$. For each value of $k$, the time delay is then found as the lag maximizing the cross-correlation function between $x_1$ and $x_2$.

Once these delays have been determined, the particle velocity in the direction of the transducer, is computed as

$$v[k] = \frac{n_0[k]}{T_s/c}$$ (4)

where $n_0[k]$ is the time delay for window position $k$, $T_s$ is the sampling time, and $c$ is the speed of sound in the fluid.
To obtain better estimates of the particle velocity profiles, the above procedure is repeated 512 times, each resulting in an estimated velocity profile. These are then combined by computing the arithmetic mean of all estimated velocity profiles, as

\[ \bar{v}[k] = \frac{1}{152} \sum_{i=1}^{152} v_i[k] \]  

This method is described in more detail in e.g. [1], where also methods for robust signal processing of weak signals is investigated.

**B. Ultrasonic Velocity Profiling in two dimensions**

To be able to acquire the particle velocity in two dimensions, two transducers are needed to create two velocity vectors. The combined velocity is calculated using three planes; one plane defined by each of the two transducers, and the third plane defined by assuming that the flow velocity perpendicular to both transducers is zero.

The scalar particle velocity \( v_i \) in the direction of each transducer \((i = 1, 2)\) is calculated using UVP, as above. Let \( \hat{n}_i \) be a unit vector in the axial direction of each of the transducers. The velocity vector, in the axial direction of the transducer, is then calculated as \( \hat{v}_i = v_i \hat{n}_i \). Two unique planes are defined in velocity space by the points \( \hat{v}_1 \) and the normal vectors \( \hat{n}_1 \). Assuming the velocity in the third dimension is zero, the third plane is defined as:

\[ \hat{n}_3 = \frac{\hat{n}_1 \times \hat{n}_2}{|\hat{n}_1 \times \hat{n}_2|}, \quad v_3 = 0. \]  

Then the combined velocity vector is found in the intersection between these three planes:

\[ v_c = \frac{[\hat{V}_1 \cdot \hat{n}_1] (\hat{n}_2 \times \hat{n}_3)}{|\hat{n}_1 \times \hat{n}_2|} + \frac{[\hat{V}_2 \cdot \hat{n}_2] (\hat{n}_3 \times \hat{n}_1)}{|\hat{n}_1 \times \hat{n}_2|} \]  

Then two velocity vectors are found in the intersection.

For the presentation of the results, the measurement position \((p)\) is put in the middle between the two original measurement positions.

**C. Local solids concentration from spectral contents**

Ultrasound pulses are transmitted into the suspension and the resulting backscatter is treated as random signals carrying information about the suspension. The statistics of the signal vary with solids concentration, particle size distribution, particle density, etc. Based on short-time spectral analysis of the backscattered sound variations in local solids concentration can be visualized.

For these calculations the same sampled data as for the velocity estimations above are used. The signal, \( p[n] \), is random by nature, and due to attenuation and multiple scattering (in high concentration suspensions), the underlying random process cannot be assumed to be stationary. This means that the signal characteristics will vary as a function of depth, local mass fractions, etc. For a short segment of \( p[n] \), however, we may assume stationarity, at least in a wide sense.

So, let

\[ x_k[m] = p[k + m], \]  

where \( k \) is the position of the window, \( m = 0, 1, \ldots, M - 1 \), and the window length \( M \ll N \). In other words, \( x_k[m] \) is an \( M \) samples long segment of \( p[n] \), starting at sample \( k \). The autocorrelation sequence of \( x_k[m] \) is defined as

\[ \hat{r}_{x_k}[l] = E \{ x_k[m + l] x_k^*[m] \}. \]  

where \( (\cdot)^* \) denotes complex conjugate and \( l \) is the lag.

Assuming \( x_k[n] \) is real-valued and stationary, this can be estimated from the measurements as

\[ \hat{r}_{x_k}[l] = \frac{1}{M} \sum_{m=0}^{M-1} x_k[m + l] x_k^*[m]. \]

Thus, the autocorrelation sequence is a measure of how similar the signal is to a delayed version of itself [2].

The spectral contents, i.e. the Power Spectral Density (PSD), of \( x_k[m] \) can be estimated as the periodogram of \( x_k[m] \), which is the Fourier transform of \( x_k[n] \), given by

\[ P_{x_k}(\omega) = \sum_{l=-M+1}^{M-1} \hat{r}_{x_k}[l] w[l] e^{-j2\pi\omega l}, \]

where the angular frequency \( \omega = 2\pi f \), and \( w[l] \) is a windowing function. In this work \( w[l] \) was chosen to be an \( M \) sample Hanning window [2].

Since attenuation and backscatter intensity can be assumed to depend on the mass fraction of particles, studying \( P_{x_k}(\omega) \) as a function of depth should give an indication of changes in local particle mass fractions. Hence, for each window position \( k \), we estimate the PSD as above.

**III. Experiments**

**A. Experimental setup**

The experiments were conducted in-situ, in a pilot scale wet LIMS, at the LKAB R&D facilities in Malmberget, Sweden. The separator, a SALA counter-current separator, \( p916 \times 300 \) mm (TA-623780-2), was connected in closed loop with a vertical tank pump (Sala SPV-232) controlled by an AC drive (ABB ACS800). Both the magnetic and the non-magnetic products from the separation are circulated back to the pump sump, see Fig. 1. To keep the sensors free from settling particles a small flow is introduced close to the transducers using a peristaltic pump (Watson-Marlow 503S). This pump is stopped momentarily during all ultrasound measurements. The suspension used is a mixture of tap water and magnetite fines. The magnetite has a density of 5.2 kg/dm$^3$. Two ultrasound transducers (Olympus V306, 2.25 MHz) were mounted in the bottom of the separator tank, at a relative angle of 60°, see enlargement in Fig. 1. Each transducer is controlled by one pulser-receiver (Panametrics 5800PR and...
The received backscatter signal is collected using a digitizer (SP Devices ADQ214). Pulse timings are controlled by a micro controller (Arduino Duemilanove) running custom software. Before each ultrasound measurement the suspension temperature is measured using a digital thermometer (ASL F250 MKII). Apart from what is described above the setup is similar to the setup described in [3].

Fig. 1. Experimental setup.

### TABLE I

<table>
<thead>
<tr>
<th>Level</th>
<th>A [%vol]</th>
<th>B [rpm]</th>
<th>C [mm]</th>
<th>D [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>high</td>
<td>11</td>
<td>29.5</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>low</td>
<td>5.5</td>
<td>5.7</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>

B. Results & discussion

Fig. 2 shows the estimated particle velocity vectors (green arrows) for four different operation settings of the separator, as described in the previous section. Fig. 3 shows the corresponding power spectral densities (PSD) as function of distance to the transducer, for the wave paths (dashed black lines) labeled (I)–(IV) in Fig. 2. In all cases (I)–(IV) we can see decaying backscatter amplitude as function of depth. For a low solids concentration, homogeneous suspension, this decay is expected to be linear (in the dB scale) due to the exponential nature of ultrasound attenuation (see e.g. [4]).

In cases (I) and (II) in Fig. 3 it is clear that the decay of backscatter amplitude is non-linear. The strong increase in backscatter intensity 70 mm from the transducer in case (I), and 40 mm from the transducer in case (II), suggests that we have a build-up of magnetic particles on the surface of the rotating drum. In case (II) this material build-up is significantly thicker, which is expected since the solids concentration of the feed material is higher than in case (I).

In cases (III) and (IV), the rotational speed of the drum was set to the high level, which should increase material removal rate and prevented particle build-up. In Fig. 2c–d we note a relatively fast flow in the direction opposite the drum rotation. This suggest that we have a turbulent flow mixing the suspension, and as a consequence, the suspension solids concentration is more homogeneous. Also, since the magnetic particle build-up will be much thinner when the drum rotational speed is high, it is not visible in the figures.

IV. CONCLUSIONS

In this paper we have demonstrated the applicability of an ultrasound pulse-echo technique for in-situ monitoring of solids concentration variations and particle velocities inside of a wet low-intensity magnetic separator. The technique adds valuable insight to how the flow patterns are affected by adjusting the operational settings of the separator.

ACKNOWLEDGMENTS

Hjalmar Lundbohm Research Centre (HLRC) is gratefully acknowledged for its financial support. Esa Wikström at LKAB R&D and Tomas Olausson and the staff at LKAB Quality service in Malmberget are acknowledged for support before and during the experimental campaign using their pilot scale wet LIMS.

REFERENCES


Fig. 2. Estimated particle velocity profiles for four different running conditions. In (a) and (c), the solids concentration was set to the low level and the drum speed, weir distance and magnet distance were all set to high in (a) and to low in (c). This was then repeated for (b) and (d), but for the high solids concentration. See Table I.

Fig. 3. Power-spectral density of ultrasound backscatter, as function of distance from the ultrasound transducer. (I)–(IV) correspond to the labels in Fig. 2.
Paper VII

Monitoring Mineral Slurry Flow using Pulse-Echo Ultrasound

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Monitoring Mineral Slurry Flow using Pulse-Echo Ultrasound

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Abstract
Ultrasound based flow measurement methods have a large potential for the mining industry and its processing plants. Ultrasound travel through dense suspensions and is not affected by the magnetic fields sometimes present in this type of equipment.

A cross-correlation based method is used for localized particle velocity measurements in one and two dimensions. Simultaneously, using the same data, information about local particle concentration is extracted from the power spectral density of the backscattered signal. Experiments are carried out both in simplified geometry and in full scale equipment in an iron ore pilot benefication plant.

In the simple geometry it is possible to assess the precision of the methods by comparing the measurements to theory and numerical simulations. The results from the pilot plant experiments show that these methods can be applied to real world processes.

Keywords: Flow monitoring, Mineral slurry, Particle velocity, Ultrasonic velocity profiling, Suspension solids concentration, Power spectral density

1. Introduction
In the mining industry, which is a highly automated process industry, mineral material is transported between, and inside, various equipment to...
grind and separate the material into the desired fractions. This transport is
done both in dry state and in suspension with water. With time the demands
on the different processes increase, both because the simple ores are already
mined, and also because of more restrictive environmental regulations. This
gradual change calls for more precise methods in process monitoring and
control.

In this paper the possibilities for using pulse-echo ultrasound in high
density mineral suspensions are investigated. A windowed cross-correlation
based method is used for localized particle velocity measurements in one and
two dimensions, and the power spectral density (PSD) is studied to extract
information about local particle concentration. It is also shown how these
methods can be combined and used in standard process equipment. The
context selected for evaluation of these methods is a process common in
mineral processing; wet low-intensity magnetic separation (LIMS).

1.1. Background

In the mining industry, and elsewhere, ferromagnetic particles are sepa-
rated from other solid particles using wet LIMS. A suspension of the ferro-
magnetic mineral magnetite and non-magnetic gangue minerals in water are
pumped into the separator tank, and the magnetite is extracted using mag-
netic forces. This separation process creates non-trivial flow patterns, and it
is of interest to monitor the flow patterns inside the separator structure, as
well as the magnetic particle build-up created by the magnetic field. Since
the suspension is essentially opaque and the solids concentration rather high,
this is a demanding environment for flow measurements, and no means for
internal flow measurements exist today.

To gain a deeper understanding of the process of wet LIMS, measurements
of internal particle flow are needed. To obtain quality data the following
needs were identified:

1. The sensor is required to operate from one direction only, since the
separator design allows physical access to the flow from one side only
(see Fig. 2).

2. A technique capable of penetrating opaque and high density suspen-
sions is required.

3. Some degree of spatial resolution is needed, since direction and velocity
of the flow can vary in the volume of interest.
4. A non-intrusive technique is preferred since the best results are obtained if the flow is not disturbed, and since the suspension flow could be harsh on the sensors.

5. Information about both local flow speed and local suspension concentration variations is desired.

Based on the identified needs two pulse-echo ultrasound based methods were selected and combined.

There are three main categories of ultrasound based 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 [1], [2]. The first method used here is a speckle correlation technique, where cross-correlation between ultrasound echoes is used to estimate particle velocity in flow of suspensions. Already in 1976 Dotti et al. [3] used a similar method to measure blood flow velocity. Carlson and Ing [4] used a speckle correlation technique to measure 2d particle velocity profiles in flow of magnetite suspensions.

Measuring the intensity of the backscattered signal using various methods make it possible to extract information about local solids concentration in the suspension. Carlson and Martinsson [5] used a transmitter-receiver setup to compare measurements to single scattering theory. A linear dependency was found between the coefficient of excess attenuation and suspension solids concentration, for solids concentrations up to approx. 2.6 vol% solids. Hunter et al. [6] studied settling and movement of the settling interface (see Fig. 4). The backscatter strength was found to have a linear decay, on a dB scale, with suspension depth. This relation was found in homogeneous suspension at a distance of 40-160 mm from the transducer. Hunter et al. [7] compared experimental data to backscatter theory, and their results suggested that the single scattering theory is invalid for systems with particle concentrations greater than 0.1 vol%. Wöckel et al. [8] used a narrow measurement cell, resembling what can be found e.g. in analytical instruments. A linear relationship was found between suspension solids concentration and the signal amplitude standard deviation. The measurement depth was e.g: 16 mm in a suspension of 4.5 vol% solids, and 5 mm in a suspension of 30 vol% solids. Weser et al. [9], [10] used the same setup as [8] to study how the peak backscatter amplitude increase with mean particle size. When using a 6 MHz transducer good correlation was found for mean particle sizes between
10-54 μm, and when using 10 and 14 MHz transducers good correlation was found for particle sizes of 7-23 μm.

2. Experimental setups

The experiments presented later are carried out using two experimental setups. The main part of the first setup is a rectangular flow cell, operated in the mineral processing laboratory at Luleå university of technology. The second setup is built around a pilot scale wet LIMS in the pilot plant at the LKAB R&D facilities in Malmberget, Sweden.

2.1. Rectangular flow cell

The rectangular flow cell in Fig. 1 has a depth of 50 mm, width of 75 mm and length of 1 m. The flow is driven by a progressing cavity pump capable of supplying a bulk flow rate of up to 1 m/s in the flow cell. One transducer can be fitted at a 45 degree inclination at one end of the cell. The suspension is a mixture of magnetite powder and tap water. The magnetite has a density of 5.0 kg/dm$^3$, median particle diameter of 29 μm, and 85 wt% of the particles pass a 45 μm sieve.

The measurements are made using four immersion transducers with center frequencies; 1.0 MHz (Olympus V303), 2.25 MHz (V306), 3.5 MHz (V382), and 5.0 MHz (V309). The transducers are controlled via a pulser-receiver (Panametrics 5800PR) and the backscatter signal is collected using a digitizer (SP Devices ADQ214). Before each ultrasound measurement the suspension temperature is measured using a digital thermometer (ASL F250 MKII). To keep the sensors free from settling particles and air bubbles a small peristaltic pump (Watson-Marlow 503S) is used. The setup has been described in more detail in [11].

2.2. Pilot scale separator

The pilot scale experiments were conducted in-situ, in a pilot scale wet LIMS, at the LKAB R&D facilities in Malmberget, Sweden. The separator, a SALA counter-current separator, $\varnothing$916 x 300 mm (TA-623780-2), was connected in closed loop with a vertical tank pump (Sala SPV-232) controlled by an AC drive (ABB ACS800). Both the magnetic and the non-magnetic products from the separation are circulated back to the pump sump, see Fig. 2. To keep the sensors free from settling particles a small flow is introduced close to the transducers using a peristaltic pump (Watson-Marlow 503S). This pump
is stopped momentarily during all ultrasound measurements. The suspension used is a mixture of tap water and magnetite fines. The magnetite has a density of 5.2 kg/dm$^3$, median particle diameter of 35 μm, and 63 wt% of the particles pass a 45 μm sieve.

Two ultrasound transducers (Olympus V306, 2.25 MHz) were mounted in the bottom of the separator tank, at a relative angle of 60° or 90°, see enlargement in Fig. 2. Each transducer is controlled by one pulser-receiver (Panametrics 5800PR and 5072PR). The received backscatter signal is collected using a digitizer (SP Devices ADQ214). Pulse timings are controlled by a micro controller (Arduino Duemilanove) running custom software. Before each ultrasound measurement the suspension temperature is measured using a digital thermometer (ASL F250 MKII). Apart from what is described above the setup is similar to the setup described in [12].

3. Methods

Four experiments were used to evaluate the potential of ultrasound pulse-echo measurements in mineral suspensions in arbitrary geometries. Table 1 contains a collection of the most important measurement and signal processing parameters in the following experiments:
1. Velocity measurements in the rectangular flow cell.

2. Suspension settling in the rectangular flow cell.

3. Capture of magnetic material by the permanent magnet in the rectangular flow cell.

4. Flow monitoring in the pilot scale magnetic separator.

3.1. Velocity measurements in the flow cell

In these experiments magnetite suspensions are pumped through the rectangular flow cell (Fig. 3a), at a constant flow rate, while the local particle velocity is measured.

To ensure sufficient mixing of the suspension (by turbulence) the flow speed is kept at 1 m/s for at least 60 s before each measurement. During the data acquisition process, controlled by a MATLAB script, ultrasound pulses are transmitted into the suspension and the backscattered echo is
Table 1: Measurement system and signal processing parameters. Parameter set 1a and 1b was used during the measurements in undisturbed flow in the flow cell, set 2 in settling suspension, set 3 during magnetic capture, and set 4 in the pilot scale LIMS.

<table>
<thead>
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<th>Parameter set</th>
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<th>1b</th>
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<th>4</th>
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<td>1, 2.25, 3.5</td>
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<td>100</td>
<td>200</td>
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<td>Sample bit depth [bit]</td>
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</table>

sampled. The sampled data contains information about the particles in the flow, and using the signal processing methods described below (in section 4), it is possible to estimate local particle velocity and get information about changes in local solids concentration.

To assess the potential of the method several parameters were varied. The factors varied were e.g; the suspension flow rate, the suspension solids concentration, and the transducer center frequency. The measurements were also compared to a numerical simulation. The measurement method and the results are described in detail in [11] and the effects of using different averaging methods are studied in [13].

3.2. Concentration measurements during suspension settling in the flow cell

The purpose of these experiments is to study if the local solids concentration in a settling suspension can be monitored using pulse-echo ultrasound. During these experiments magnetite suspensions are pumped through the rectangular flow cell (Fig. 3a). When the pump is stopped, the ultrasound measurement system is used to monitor the settling process. The settling creates a region with a strong concentration gradient; a settling interface, see Fig. 4. If the particle concentration is low the settling proceeds at a
Figure 3: Experiments in the rectangular flow cell. a) Setup used when studying undisturbed flow and settling suspension. b) Setup used when studying capture, and build-up, of magnetic particles by a set of permanent magnets. The arrow marked $\mathbf{M}$ indicates direction of magnetization, and the red arrow marks where the field strength is measured.

Figure 4: Suspension settling, dark color indicates high particle concentration. Before time 0 there is a turbulent flow through the flow cell. As the pump is decelerated to a stop the suspension starts to settle, and sediment begins to form on the bottom of the cell.

constant velocity, but as the solids concentration below the settling interface becomes high enough the style of settling changes from free to hindered settling, reducing the settling velocity. The data acquisition process is initiated as the pump starts to decelerate. Data acquisition is done according to the same procedure as described above, in section 3.1. By varying the suspension solids concentration different cases are studied, this has been described in more detail in [14] and [15].

3.3. Flow monitoring during capture of magnetic material in the flow cell

In this experiment the possibilities to use ultrasound to monitor the build-up of magnetic material in a static magnetic field is investigated. Magnetite
suspensions of varying solids concentration are pumped through the flow cell, and an assembly of neodymium magnets (grade N35) is introduced to attract and capture the ferromagnetic magnetite particles. Three magnets of dimensions 45x25x10 mm were used together with two 6 mm plastic spacers, see Fig. 3b. The ultrasound based measurements was used to measure the ultimate thickness of the magnetic build-up, when the capturing process had reached its steady state (after 60 s). Otherwise data acquisition is done according to the same procedure as described above, in section 3.1.

By varying the suspension flow rate, and the magnetic field strength in the flow cell different conditions were studied. The suspension flow velocity was varied between 0.5 m/s and 1.0 m/s. The magnetic field strength was varied between 46 mT and 166 mT by placing 10 mm plastic spacers between the magnets and the flow cell. The field strength was measured at a distance corresponding to right below the upper wall of the flow cell, using an empty flow cell.

3.4. Flow monitoring in the pilot scale separator

In this experiment the methods described above are adopted for measurements inside a magnetic separator in a pilot concentrator. The magnetic separator is run at realistic conditions, and a pair of transducers are used to monitor the internal flow. By using two transducers, mounted at an angle, particle velocity and direction in two dimensions (2D) can be estimated. Two measurements, as described above, are made simultaneously, in approximately the same volume of flow, from two directions. To avoid interference between the transducers only one of the two transducers are transmitting during each measurement. 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. 5, both transducers can be sampled in the same time span.

Four factors important to machine performance were selected and varied in a designed experiment. The factors included are; the feed solids concentration, the drum rotational speed, the concentrate overflow weir distance, and the magnet assembly angle. The method is similar to the method used in [12] in a laboratory scale separator.
4. Signal processing

In this section theory regarding the calculation of the simultaneous velocity and concentration profiles are presented. It has been divided into three parts; the estimation of velocity profiles, the combination of velocity profiles, and the estimation of solids concentration variations.

4.1. Ultrasonic velocity profiling

The method used for particle velocity measurements is called ultrasonic velocity profiling (UVP). In each measurement, the ultrasound transducer transmits a short pulse into the flow. The backscattered sound from the particles in the suspension is then sampled at a sampling interval $T_s = 1/f_s$ and stored as the signal

$$ p_i[n] = p_i(nT_s), n = 0, 1, \ldots, N - 1. \quad (1) $$

Two of these signals $(i = 1, 2)$ are acquired at a pulse-repetition frequency (PRF) so that the time between the two acquisitions is $T_{PRF} = 1/PRF$. If the PRF is high enough, we can assume that the particles in the interaction volume has moved 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 $T_{PRF}$. Finding this time delay can be done by a simple cross correlation of the two echoes, as

$$ n_0 = \arg \max_m XC \quad (2) $$
i.e. the time delay between the echoes is found at the lag $m$ between the echoes that maximizes the cross-correlation between them. Since the particle velocity varies throughout the flow this time delay will depend on the depth through the flow; displacement of the flow has to be considered a function of depth. We therefore compute the cross-correlation between short segments of $p_1[n]$ and $p_2[n]$, thus resulting in one time delay estimate for each such pair of segments. In other words, let

$$x_1[k] = \{p_1[k + 1], p_1[k + 2], ..., p_1[k + M]\}$$

$$x_2[k] = \{p_2[k + 1], p_2[k + 2], ..., p_2[k + M]\}$$

be an $M$ sample long window from $p_1[n]$ and $p_2[n]$, respectively, where $k = 0, 1, \ldots, N - M - 1$ is the window position. For each value of $k$, the time delay is then found as the lag maximizing the cross-correlation function between $x_1$ and $x_2$, as in Eq. 2. Once these delays have been determined, the particle velocity is computed as

$$v = n_0 \frac{T_s c}{2T_{PRF}}$$

where $n_0$ is the time delay, $T_s$ is the sampling time, and $c$ is the speed of sound in the fluid. To obtain better estimates of the particle velocity profiles, the above procedure is repeated $Q$ times, each resulting in an estimated velocity profile. These are then combined by computing the arithmetic mean of all estimated velocity profiles, as

$$v_m = \frac{1}{Q} \sum_{i=1}^{Q} v_i$$

For the 1D-measurements in the flow cell the velocity is projected onto the horizontal axis of the flow cell, using the inclination angle between the transducer and the main flow direction ($45^\circ$). This method is described in more detail in [11], and in [13] methods for robust signal processing of weak signals are investigated.

4.2. Ultrasonic velocity profiling in two dimensions

To acquire the particle velocity in two dimensions, two transducers are needed to create two velocity vectors. The combined velocity is calculated using three planes; one plane defined by each of the two transducers, and a third plane defined by assuming that the flow velocity perpendicular to both transducers is zero.
The scalar particle velocity \( v_t \) in the direction of each transducer \((t = 1, 2)\) is calculated using UVP, as above. Let \( \hat{n}_t \) be a unit vector in the axial direction of each of the transducers, then a velocity vector, in the axial direction of the transducer, is calculated as \( V_t = v_t \hat{n}_t \). Using \( V_t \) as points and \( \hat{n}_t \) as normal vectors two planes are defined in velocity space, and the third plane is defined as:

\[
\hat{n}_3 = \frac{\hat{n}_1 \times \hat{n}_2}{\|\hat{n}_1 \times \hat{n}_2\|}, v_3 = 0.
\] (6)

Finally the combined velocity vector is calculated as the point of intersection between these three planes;

\[
v_c = \frac{(V_1 \cdot \hat{n}_1) (\hat{n}_2 \times \hat{n}_3) + (V_2 \cdot \hat{n}_2) (\hat{n}_3 \times \hat{n}_1) + (V_3 \cdot \hat{n}_3) (\hat{n}_1 \times \hat{n}_2)}{|\hat{n}_1 \hat{n}_2 \hat{n}_3|} \] (7)

For the presentation of the results, the measurement position \((p)\) 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. 2.

### 4.3. Local solids concentration from spectral contents

Ultrasound pulses are transmitted into the suspension and the resulting backscatter is treated as random signals carrying information about the suspension. The statistics of the signal vary with solids concentration, particle size distribution, particle density, etc. Based on short-time spectral analysis of the backscattered sound variations in local solids concentration can be visualized.

For these calculations the same sampled data as for the velocity estimations above are used. The signal, \( p[n] \), is random by nature, and due to attenuation and multiple scattering (in high concentration suspensions), the underlying random process cannot be assumed to be stationary. This means that the signal characteristics will vary as a function of depth, local solids concentration, etc. For a short segment of \( p[n] \), however, we may assume stationarity, at least in a wide sense. These short segments are defined as in Eq. 3 above, and \( m = 0, 1, \ldots, M - 1 \) is the sample position in the window.

The autocorrelation sequence of \( x_k[m] \) is then defined as

\[
r_{x_k}[l] = E \{ x_k[m+l] x_k^*[m] \},
\] (8)
where \((\cdot)^*\) denotes complex conjugate and \(l\) is the lag. Assuming \(x_k[m]\) is real-valued and stationary, this can be estimated from the measurements as

\[
\hat{r}_{x_k}[l] = \frac{1}{M} \sum_{m=0}^{M-1} x_k[m + l] x_k[m].
\]  

Thus, the autocorrelation sequence is a measure of how similar the signal is to a delayed version of itself [16].

The spectral contents, i.e. the PSD, of \(x_k[m]\) can be estimated as the periodogram of \(\hat{r}_x[l]\), given by

\[
P_{x_k}(\omega) = \sum_{l=-M+1}^{M-1} \hat{r}_{x_k}[l] w[n] e^{-jl\omega},
\]

where the angular frequency \(\omega = 2\pi f\), and \(w[n]\) is a windowing function. In this work \(w[n]\) was chosen to be an \(M\) sample Hanning window [16].

Since attenuation and backscatter intensity can be assumed to depend on the concentration of particles in the suspension, studying \(P_{x_k}(\omega)\) as a function of depth should give an indication of changes in the local solids concentration. Hence, for each window position \(k\), we estimate the PSD as above.

5. Results and discussion

To demonstrate the potential in using pulse-echo ultrasound to monitor flow of mineral suspension during various flow conditions, and in arbitrary geometries, a selection of results are presented in this section. Particle velocity and concentration measurements in the flow cell, and also results from the combined measurements in the real world application are presented.

5.1. Velocity measurements in the flow cell

In these experiments 1D UVP is used to measure particle velocity in suspension flowing in the rectangular flow cell, while varying the suspension solids concentration, the mean flow rate, and the transducer center frequency. The results are used to compare the performance of transducers with four specified center frequencies between 1 MHz and 5 MHz. Solids concentrations between 5 vol\% and 9 vol\% solids was used, and the mean flow velocity was varied between 0.75 m/s and 1 m/s. The main parameters of the measurement system are included in Table 1; column 1a is used in Fig. 6 and Fig. 7a-b, and column 1b in Fig. 7c-f.
Initially a few experiments was carried out at low suspension solids concentration, approximately 0.5 and 2 vol% solids, and a transducer with a center frequency of 5 MHz was used. These measurements are compared to numerical simulation results from a computational fluid dynamics (CFD) model, in Fig. 6. The CFD-model was built in Comsol Multiphysics 4.3 (www.comsol.com). The model consists of a duct with the same dimensions as the flow cell where water (at 20°C) flows with an average velocity of 1.0 m/s. The software-generated physics controlled mesh consists of $535 \cdot 10^3$ elements. The $k-\epsilon$ turbulence model is used and all other settings are left at their defaults. Using a 5 MHz transducer, and a solids concentrations of 2 vol% or lower, UVP is capable of measuring through the available depth of 50 mm, and the measurements and the simulation are in good agreement.

In Fig. 7a-d the suspension has a solids concentration of approximately 4.7 vol% solids, corresponding to 20 wt% solids. 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 approximately 27 mm is reached for the 3.5 MHz transducer and 22 mm for the 5 MHz transducer. In the combination of flow conditions, solids concentrations, and particle size distribution used in this work, the pulses from the 1 MHz transducer does not interact enough with the suspension 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. 7e-f, the 2.25 MHz transducer still produces the most reliable results and it is possible to reach a depth of almost 30 mm.

5.2. Concentration measurements during suspension settling in the flow cell

In these experiments a magnetite suspension is pumped through the rectangular flow cell. When the pump is stopped the ultrasound based methods are used to monitor the sedimentation process. Measurements are made through the cell depth of 50 mm, in the concentration range of 0.24 to 7.5 vol% (1.2-29 wt-%) solids. The backscattered signal is acquired at a pulse-repetition frequency of 200 Hz, which enables us to study rapid variations in local solids concentration. The main parameters of the measurement system are included in column 2 of Table. 1.

Nine snapshots of the settling process are shown in Fig. 8. The first snapshots (in the top images, Fig. 8a, d, and g), are taken just shortly after the pump begins to decelerate (at time $t_0$). Then there is a time lapse with
\[ \Delta t = 5.0 \text{ s} \] between the images, showing the settling process, e.g: Fig. 8a–c for the 7.5 vol% solids case. The backscatter PSD is calculated as the mean over 40 measurements (0.2 s). The transmitted ultrasound pulse will naturally create a backscatter spectrum with highest intensity around its center frequency. Low local solids concentration gives less backscatter, and a lower intensity. Interpreting this information it is possible to qualitatively follow variations in local solids concentration, as function of depth and time. An increase in backscattered intensity indicates an increase in solids concentration, e.g: when the transmitted pulse reaches the settling interface the locally increased solids concentration creates a strong echo. In the high solids concentration region of the suspension, the signal is strongly attenuated.

By using the described method it is possible to qualitatively follow variations in local particle concentrations, as a function of depth and time, for suspensions with a wide range of solids concentrations. In a settling suspension it is possible to follow the settling interface, e.g. the arrows in Fig. 8b, e, and h. As expected, the settling velocity varies with particle concentration, due to hindered settling.

5.3. Flow monitoring during capture of magnetic material in the flow cell

In these experiments a set of magnets is added to the rectangular flow cell, and the ultrasound system is used to monitor the build-up of magnetic material at the top wall of the flow cell. Initially the suspension is pumped...
Figure 7: Suspension flow velocity measured in the flow cell at varying mean suspension solids concentration, and transducers center frequency. Each figure include two profiles, measured in a flow with a bulk flow rate of 0.75 m/s and 1.0 m/s. The red dashed lines indicate where the measured profiles start to deviate from the expected results. a) 5 vol% solids, 1 MHz transducer. b) 5 vol% solids, 2.25 MHz transducer. c) 5 vol% solids, 3.5 MHz transducer. d) 5 vol% solids, 5 MHz transducer. e) 9 vol% solids, 1 MHz transducer. f) 9 vol% solids, 2.25 MHz transducer.
Figure 8: Backscatter PSD for three solids concentrations at three times ($\Delta t = 5 \text{s}$) during suspension settling. The vertical axis show the vertical distance from the upper wall of the flow cell, down through the suspension. The arrows indicate approximate position of the settling interface, see Fig. 4.
through the cell at high velocity to ensure sufficient mixing. Then an assembly of neodymium magnets were added on top of the flow cell, flow velocity and backscatter PSD was measured after the capture process had reached steady state (60 s after adding the magnets). The main parameters of the measurement system are included in column 3 of Table. 1.

In Fig. 9 and Fig. 10 the left figures show the local suspension velocity measured during steady state. The suspension flow is diverted downwards by the stationary magnetic build-up. One standard deviation in the measurement, partly due to turbulence, is also included (dashed green). The middle figures show the mean backscatter PSD, calculated as in section 4.3, and showing mean intensity for frequencies between $0.5f_c$ and $2f_c$. The transition from suspension flow to magnetic build-up is indicated by a small increase in local PSD. The figures to the right show the space-derivative of the data in the middle figure. The red horizontal line marks the approximate position of the transition between suspension flow and magnetic build-up created by the stationary magnet. The line is positioned where the mean backscatter PSD starts to increase (change turn positive, seen from the transducer, in the figures to the right). This criteria is robust for the lower levels of suspension solids concentration. At higher levels of solids concentration, however, the intensity is never increasing, see Fig. 10c.

The increase in mean PSD is caused by the increased reflection from the dense build-up. Since the transmitted pulse is also strongly attenuated in the build-up the increase in mean PSD is also followed by a strong decrease. These experiments show that backscatter PSD can be used to monitor the thickness of magnetic build-up. However, for this method to work there has to be a distinct difference in the solids concentration of the flowing suspension and the stationary build-up. With this material the magnetic build-up is expected to have a solids concentration of approximately 35 vol%. From Fig. 9 it is apparent that the ultimate build-up thickness increase with magnetic field strength, as expected.

5.4. Flow monitoring in the pilot scale separator

In these experiments the presented methods are evaluated in the pilot scale wet LIMS. Particle velocity and concentration measurements are made on the concentrate side of the separator, after the separation process has reached steady state (120 s). The effect of varying four factors important to process operating conditions are studied. The main parameters of the measurement system are included in column 4 of Table. 1, a window length
Figure 9: Profiles showing suspension velocity, mean of PSD, and change in mean PSD, at varying magnetic field strength. The suspension solids concentration is 1.4 vol% solids, the mean flow velocity is 0.75 m/s, and a transducer with center frequency 2.25 MHz was used. In the velocity plots to the left one standard deviation of the velocity measurements (partly due to turbulence) is included (dashed green). The magnetic field strength is: a) 46 mT. b) 84 mT. c) 166 mT.
Figure 10: Profiles showing suspension velocity, mean of PSD, and change in mean PSD, at varying suspension solids concentration. The magnetic field strength is 166 mT, the mean flow velocity is 0.75 m/s, and a transducer with center frequency 2.25 MHz was used. In the velocity plots to the left one standard deviation of the velocity measurements (partly due to turbulence) is included (dashed green). The mean suspension solids concentration is: a) 0.2 vol% solids. b) 0.8 vol% solids. c) 2.8 vol% solids.
of 1000 samples is used for calculating the PSD, and 1600 samples for the 2D UVP.

Figure 11 shows the estimated particle velocity vectors for four operation settings of the separator. Figure 12 shows the corresponding PSD as function of distance to the transducer, for the wave paths (dashed black lines) labelled (I)–(IV) in Fig. 11. In all cases (I)–(IV) the backscatter amplitude decays as function of depth. For a low solids concentration, homogeneous suspension, this decay is expected to be linear (in the dB scale) due to the exponential nature of ultrasound attenuation (see e.g. [5]).

In cases (I) and (II) in Fig. 12 it is clear that the decay of backscatter amplitude is non-linear. The strong increase in backscatter intensity 70 mm from the transducer in case (I), and 30 mm from the transducer in case (II), suggests a build-up of magnetic particles on the surface of the rotating drum. In case (II) this material build-up is significantly thicker, which is expected since the solids concentration of the feed material is higher than in case (I).

In cases (III) and (IV), the rotational speed of the drum was set to the high level, which should increase material removal rate and prevent particle build-up. It is also likely that the increased rotational speed of the drum brings more water into the zone where the measurements are made. In Fig. 11c–d we note a relatively fast flow in the direction opposite the drum rotation, due to dewatering of the concentrate. A flow velocity of approximately 0.5 m/s suggest a turbulent flow mixing the suspension, and as a consequence, the suspension solids concentration is more homogeneous. Also, since the magnetic particle build-up will be much thinner when the drum rotational speed is high, it is not visible in the figures.

The deviations seen in Fig. 11, between the measurements at the two relative sensor angles (60° or 90°), are believed to be mainly due to experimental error in the control of the separator. This, since the pump and the separator are stopped, and the sensor positions are changed manually, between each measurement. The steeper angle (60°) provides a deeper reach, but on the other hand the 90°–measurements could give better precision.

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.
Figure 11: Internal flow profiles from pilot scale wet LIMS. Flow velocity profiles measured using 60° angle (green arrows) and 90° angle (blue arrows) between transducers. a) All factors at their low level. b) High feed solids concentration, remaining factors at their low level. c) Low feed solids concentration, remaining factors at their high level. d) All factors at their high level.
Figure 12: Power-spectral density of ultrasound backscatter, as function of distance from the ultrasound transducer and frequency. (I)–(IV) correspond to the measurements at the labels in Fig. 11.

6. Conclusions

If the flow has a natural direction, through a pipe or a narrow duct, 1D UVP with one transducer can be used to get good estimates of local flow velocity. If two transducers are used, also the direction of flow in two dimensions can be estimated. The limitation is that both transducers need to target approximately the same volume of the flow. By having more advanced equipment, with movable transducers or transducer arrays, the measurement volume could be increased. Even though this was not tested, it should be possible to extend the 2D UVP method to three dimensions by using three transducers.

The experiments with settling suspension and capture of magnetic particles show that the pulse-echo method is capable of monitoring the transition between suspension of low and high solids concentration. The method is robust for a wide range of suspension flows. This is valuable in magnetic separation since it can provide a direct measure of the material build-up inside the separator.

Finally the methods were evaluated in a real world separator in a pilot concentrator. Using the presented methods it is possible to monitor variations in solids concentration and particle velocities inside of the separator. The methods adds valuable insight to how the flow patterns are affected by
When applied to flows of mineral suspensions of high solids concentration, similar to those in wet LIMS, the method is unique in combining:

- Simultaneous estimation of local particle velocity and concentration.
- Low flow disturbance.
- Operation by a single transducer (two for 2D-measurements).
- Good spatial resolution.
- Operation in opaque, relatively dense, suspensions.
- Possibility to study dynamic processes (measurement rate > 1000 Hz).

In all of these experiments the penetration depth needed from the measurement methods has been between 50 mm and 100 mm, and the suspension used has been made up of water and finely ground mineral powder. In this environment the preferred transducer center frequency has proven to be in the range 2-3 MHz, then a homogeneous solids concentration of about 5 vol% can be handled with good result. By shortening the measurement distance solids concentration of at least 10 vol% can be handled.

Only ten years ago these methods were too computationally demanding, and thus too expensive, to be feasible for process monitoring in the process industry. But as the price on computing power is decreasing this type of methods should find more and more applications. This measurement method has already gained attention from industry, since it is generally applicable to narrow channel flows reachable from only one access point.

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8. References


