Detection of the pulp-froth interface using the ultrasound transit time technique

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\textbf{ARTICLE INFO}

Keywords:
- Lab-scale flotation
- Level height detection
- Pulp-froth interface
- Ultrasound transit time technique

\textbf{ABSTRACT}

The vertical position of the pulp-froth interface in a flotation cell is an important parameter in froth flotation processes which needs to be controlled in situ. For this purpose, we introduce the ultrasound transit time technique (UTTT), a non-invasive technique for detecting and measuring the position of this interface. Based on lab-scale experiments, the method is evaluated for a pulp-air and a pulp-froth interface. The technique was found to be well applicable in pulp with up to 21\% particle mass fraction. In a container with 80 mm height the accuracy is found to equal 1 mm.

1. Introduction

Froth flotation is an important process in mining to extract valuable mineral particles from valueless gangue particles. A number of parameters are relevant for controlling froth flotation processes, including the bubble size distribution, the bubble surface area flux, and the formation of the pulp-froth interface (Yianatos and Henríquez, 2007; Vinnett et al., 2009; Leiva et al., 2010). The vertical position of the pulp-froth interface has a strong influence on the extraction of pulp and thus, on the grade of the concentrate.

To detect the pulp-froth interface, pressure sensors, conductivity and capacitance probes, microwave radar, ultrasound transmitters and optical measurements have been employed (Hamilton and Guy, 2001; Jampana et al., 2009; Shean and Cilliers, 2011). Pressure sensors cannot be applied directly to the pulp. Instead, they are attached to side tubes. This configuration enables the interface to be continuously detected over a certain height range (Hamilton and Guy, 2001). Capacitance probes use the difference in the dielectric constant between air and aqueous solution. They can either be applied directly to the pulp or to a side tube (Hamilton and Guy, 2001). Conductivity probes rely on the difference in the electric conductivity between pulp and froth. An array of probes can be installed equidistantly along a vertical side-tube. The resulting vertical position thus is discretized to the vertical position of the probes (Van Deventer et al., 2001; Maldonado et al., 2008). The signals from microwave radar and ultrasound transmitters are sent vertically through the pulp. At the pulp-froth interface (Shean and Cilliers, 2011) they are reflected by a floating object back into the pulp. There, they are recorded and the time of flight yields the vertical position of the floating object. The accuracy of the measurements is limited by the assumption that the pulp density and thus, the local speed of sound, is uniform (Maldonado et al., 2008). Another approach to apply ultrasound is to measure from the top of a flotation cell. Here, the transducer, positioned above the froth, emits pulses with a frequency in the kHz range, which are reflected by an object floating on the top of the froth (Bishop, 1991). The interface can be detected visually if optical access to the cell can be enabled (Jampana et al., 2009).

For use in lab-scale flotation cells, capacitance and pressure probes, as well as the float techniques, are able to detect the position of the pulp-froth interface to within $\pm 1$ mm (Hamilton and Guy, 2001). These methods are more invasive. Also the direct contact with the medium could be disadvantageous in some applications.

The present work focuses on the application of a noninvasive ultrasound technique, known as the ultrasound transit time technique (UTTT), for detecting the pulp-froth interface. The transducers are coupled to the pulp through the bottom of the tank. To the best of our knowledge, this coupling method has not been applied before. UTTT originates from non-destructive material testing, and was developed in particular in connection with advanced flowmeters (Moore et al., 2000;...
Mahadeva et al., 2009). It measures the time of flight \( t_f \) for a sound pulse to travel from an ultrasound transducer to a certain reflecting object and back to the transducer. Knowing the speed of sound \( c \), this yields the distance between the transducer and the reflecting object's position:

\[
s = \frac{c t_f}{2}.
\]

UTTT was utilized already in a multi-phase flow to detect bubbles and to measure their trajectories and diameters, or the tilt angles of ellipsoidal bubbles in water and in liquid metals. A detailed comparison with other techniques, such as optical measurements and X-ray radiography, has demonstrated the accuracy of UTTT for measurements in multiphase flows (Richter et al., 2015; Richter et al., 2017; Richter et al., 2018). Also, ultrasound echoes from foam structures have been used to measure the velocity of foam (Nauber et al., 2018).

The motivation for the present study is a quantitative evaluation of the capability of UTTT to detect the pulp-froth interface directly, without relying on a floating object. For that purpose, we apply UTTT to three different experiments. Firstly, stirred particle suspensions with different particle fractions, secondly, the stirred particle solution with air bubbles, and thirdly, stirred particle suspensions with air bubbles and frother, forming froth. The speed of sound for each measurement is determined by simultaneously measuring the time of flight between a reference transducer and an artificial reflection target at a known vertical position \( h \). The accuracy of the level measured is assessed by comparison with the level as measured with a ruler.

### 2. Experimental setup

A sketch of the setup is shown in Fig. 1. The tank was made of acrylic glass and had an inner diameter of \( D = 100 \) mm and a height of \( H = 150 \) mm. Four baffles with a thickness of 10 mm were placed equidistantly at the circumference of the tank to reduce swirl and corresponding buckling of the surface. A porous tube charged with compressed air was positioned close to the bottom of the tank to respond to the bottom of the tank. The minimum impeller speed \( N_{\text{imp}} \) that prevents the sedimentation of the quartz particles is defined by the Zwietering correlation

\[
N_{\text{zw}} = S \left( \frac{\left( \sqrt{\rho_L - \rho_s} \right)^{0.45}}{\rho_s} \right)^{0.11} \left( \frac{d}{D} \right)^{2.45} D^{0.85}.
\]

where \( \nu \) is the kinematic viscosity of the liquid, \( \rho_s \) and \( \rho_l \) are the densities of the solid and liquid fraction, respectively, \( \varepsilon \) is the mass fraction of the particles and \( S \) is the Zwietering constant for the impeller (Zwietering, 1958). A correlation for a three-bladed axial impeller is given by Devarajulu and Loganathan (2016)

\[
S = 8.17 \left( \frac{C}{D} \right)^{0.329} \left( \frac{h}{B} \right)^{-0.244} \approx 3.8.
\]

With this value and a maximum \( \varepsilon \) of 21%, a critical impeller speed of \( N_{\text{zw}} = 400 \) rpm is derived. To ensure a homogeneous particle distribution, the rotation rate \( N \) of the impeller was set to \( N = 600 \) rpm > \( N_{\text{zw}} \) for all measurements.

The measuring principle of UTTT is described in detail in Andruszkiewicz et al. (2013). In the present work, the commercial defectoscope USIP 40 (G. I. Technologies) has been employed. The ultrasound transducer is acoustically coupled to a tank wall and emits a pulse of up to 5 periods with a center frequency \( f \) of 1 MHz. Pulses are repeated with a pulse repetition frequency \( f_p \) of 600 Hz. These pulses are reflected by any discontinuity in the acoustic impedance. In the present setup, discontinuities are present at the interface between the tank wall and the pulp, as well as at the pulp-air and pulp-froth interface, respectively. The echo is recorded by the same transducer, yielding the echo intensity over time. Fig. 2(a) shows a scheme of a typical amplitude diagram. The transit time is the elapsed time between the transmission of the pulse and the time at which the rising flank of the echo is detected. Fig. 2(b) and (c) show the relevant sections of typical amplitude diagrams for the echo from a pulp-air and pulp-froth interface, respectively. The secondary peaks in Fig. 2(b) are caused by multiple reflections of the pulse in the bottom wall of the tank. The corresponding time shift \( \Delta t_{\text{echo}} \approx 4.35 \mu s \) between two secondary peaks coincides with the ratio between the thickness of the bottom plate \( s_{\text{plate}} \approx 6 \) mm and the speed of sound in the plate \( c_{\text{plate}} \approx 2670 \) m s\(^{-1} \), according to

\[
\Delta t_{\text{echo}} \approx 2s_{\text{plate}}/c_{\text{plate}} \approx t_w
\]

\( \Delta t_{\text{echo}} \) also is equal to the time of flight for the first echo from the wall-

![Fig. 1. Schematic diagram of the experimental setup in top and side view. Five ultrasound transducers are attached to the bottom plate of the stirred tank in a circular arrangement.](image-url)
pulp interface $t_w$.

Five identical transducers with diameters $d_t = 10 \text{ mm}$, emission center frequency $f = 1 \text{ MHz}$, corresponding wavelength $\lambda \approx 1.5 \text{ mm}$ in pure water were employed. The product of the wave number $k = 2\pi/\lambda$ and the particle radius $a$ equals $ka = 0.7$. The transducers were attached to the bottom side of the bottom wall of the tank (cf. Fig. 1), while petroleum jelly was used as coupling gel, with a minimized film thickness and the particle radius $a$ equals $ka = 0.7$. The transducers form a circle with $D_t = 65 \text{ mm}$ diameter, protruding beyond the impeller by $10 \text{ mm}$, see Fig. 1 (b). Each transducer sends a pulse and receives the corresponding echo to measure the vertical distance $h$ from the upper side of the bottom wall of the tank to the pulp-froth and pulp-air interface, respectively,

$$h = c \frac{t_t - t_w}{2},$$

where $c$ is the speed of sound in the pulp and $t_t$ the transit time from the transducer to the interface and back. $t_w$ is the transit time to the wall-pulp interface and back (cf. Fig. 2(a)), which was measured by UTTT in a preliminary experiment. Determining $h$ from Eq. (5) also requires knowledge of $c$, which depends on the composition of the pulp.

The speed of sound $c$ in the pulp could be calculated using the approach developed by Urick (1947) for small $ka$ (viscous regime) and (Atkinson and Kytomaa, 1992; Kytomaa, 1995) for large $ka$ (inertial regime). In the present case, the parameter $ka$ is smaller than 1, which falls into the viscous regime. The corresponding equation

$$c = \sqrt{\frac{\rho}{\rho}} \left[ 1 + \frac{(1 - \rho)}{\rho} \right] \frac{1}{\sqrt{\rho}}$$

with

$$\frac{1}{\rho} = \frac{1 - \rho}{\rho} \frac{1}{k_i},$$

$$\rho = \rho s + (1 - \rho) \rho l,$$

and

$$\rho' = (1 - \rho) \rho s + \rho \rho l,$$

relies only on material properties and the mass fraction of particles $\epsilon$. With the given vertical position of the interface, $h \approx 100 \text{ mm}$, this estimates a typical transit time of $t_t \approx 135 \mu s$. The employed UTTT system offers a temporal resolution of $\sigma_t = 0.03 \mu s$, yielding a discretization uncertainty of 0.02%. However, it is difficult to determine exact values for $K$, $c$ and $\rho$ in industrial applications with varying ore composition and temperatures. Furthermore, the presence of gas bubbles reduces the speed of sound significantly, which is not considered in Eq. (6). Thus, Eq. (6) is not applicable to obtain reliable values for $c$. Instead, this quantity has been measured directly, simultaneously to the level measurements. To that end, the transit time $t_T$ is recorded, constituting the time-of-flight for a sound pulse from an additional transducer to an artificial target placed at a defined vertical position $h_T$ above one transducer

$$c = \frac{2h_T}{t_T - t_w}.$$  

Eq. (5) combined with Eq. (10) leads to

$$h = h_T \frac{t_T - t_w}{t_T - t_w}.$$  

The uncertainty of the level measurement is accessed by the deviation $\Delta h$ between $h$, the measured value from the UTTT, and $h_{tot}$, the actual filling level

$$\Delta h = h - h_{tot} = h - (h_{aq} + h_D).$$

$h_{tot}$ consists of two components. Firstly, $h_{aq}$, the level of the pure water or surfactant solution, measured with a ruler. And secondly, $h_D$, the additional height due to the addition of quartz particles. Due to higher accuracy, $h_D$ was calculated by the mass $m_a$ and the density $\rho_a$ of the added particles and the cross section $A$ of the tank

$$h_D = \frac{m_a}{\rho_a A}.$$  

The relative error $\eta$ of the measured level $h$ is calculated by

$$\eta = \frac{\Delta h}{h_{tot}}.$$  

Negative values of $\Delta h$ and $\eta$ indicate that the filling height is underestimated by the UTTT measurement.

The tank was filled with a volume of $V_{aq} = 600 \text{ ml}$ of tap water up to a height of $h_{aq} = 78 \pm 0.5 \text{ mm}$. The target was placed at a height of $h_T = 71 \pm 0.5 \text{ mm}$ above one transducer. 1.5 ml/l of frother, 4-Methyl-2-pentanol (MIBC), was added to decrease the surface tension and thus, the bubble diameter. 0.28 g/l sodium dodecyl sulfate SDS was added to create a covering froth layer when investigating a pulp-froth interface.

Different volume fractions $\phi$
of hydrophobic quartz particles (material parameters cf. Table 1) were added to the tank (cf. Table 2). Note that we plot the results over the volume fraction of particles $\phi$ while the theoretical speed of sound is calculated with the mass fraction of particles $\epsilon$.

The particles were hydrophobized using the surfactant CTAB (Sigma Aldrich, BioXtra $\geq$99%). To that end, 50 m/l of water and 18.22 mg of CTAB were added to 50 g of quartz particles. After 10 min, the particles were filtered and dried. The air flow rate was set to $Q_0 = 1.6 \text{ cm}^3\text{s}^{-1}$, which yields a superficial gas flow velocity of $J_g = 0.02 \text{ cm/s}$. The resulting mean bubble size equals approximately 3 mm, as determined from camera pictures. Measurements were carried out at a temperature of $20 \degree C$ in the pulp.

### 3. Results

In the first experiment, particle suspensions without bubbles and without froth were investigated. To that end, the tank was filled with tap water and MIBC. Then, defined amounts of particles were added consecutively to the tank while the stirrer was running. After each addition, the corresponding level was detected by UTTT with the stirrer being active. Then, the stirrer was stopped for 30 s and the particles settled. Now UTTT again was used to measure the level in the settled case. Then, the stirrer was switched on again and the next amount of particles was added. For each measurement point, 18000 individual measurements were performed during 30 s. This yields the temporal average value as well as its standard deviation.

The initial level position and the increase due to the added particles is covered well for the stirred and unstirred case for all volume fraction of particles $\phi$ (cf. Fig. 3). The averaged levels for the stirred case deviate stronger from the theoretical value than for the unstirred case. This might be due to buckling of the time-averaged interface caused by steady vortices near the baffles. Also, the standard deviation is larger in the stirred case, which presumably is caused by unsteady surface waves in the stirred case. However, the standard deviation decreases with increasing particle fraction. This could be due to the increased effective viscosity of the pulp and thus the decreased amplitude of the surface waves.

Fig. 4 shows pictures of the surface waves. Fig. 4(a) and (b) are compared to underline the fact that stirring did not generate a significant swirl changing the average shape of the interface by more than 1 mm. Fig. 4(b) shows that the interface exhibited surface waves with an amplitude of approximately 2 mm. Fig. 4(c) visualizes the unsteady wave pattern. No standing waves were observed.

In the second experiment, gas bubbles were introduced to the pulp. Similar to the first series, particles are added stepwise and the level was measured with and without stirring. Fig. 5 depicts the results of the level heights and of $\Delta h$. Again, the level and its rise due to the added particles was covered well. The values of $\Delta h$ were positive for the non stirred case as well as for the stirred one. For the non stirred case $\Delta h$ equals approximately 0.4 mm more than in the case without bubbles (see Fig. 3). This increase in volume represents the influence of the gas holdup which corresponds to a gas volume of $\approx 3 \text{ ml}$.

In the stirred case a stronger scattering of $\Delta h$ occurs, which is again caused by fluctuations of the pulp-air interface. The values of $\Delta h$ are approximately 1 mm larger than in the experiment without bubbles. This corresponds to a larger gas holdup, equal to approximately 7.5 ml, when the tank is stirred. This is in line with other investigations that stirring increases the gas holdup of such tanks.

In the third experiment, air bubbles and SDS are added, creating a stable froth layer of 10 mm thickness. The process of adding particles and measuring with and without stirring was identical to the former two experiments. Again, UTTT was capable of measuring the level and the change due to addition of particles. Fig. 6 depicts that the absolute errors $\Delta h$ of the level measurement by UTTT, plotted versus the volume fraction of particles $\phi$. The errorbars correspond to the standard deviation from temporal averaging. The small sketch right to the plot visualizes the cases. The non stirred case, where the particles are settled and the stirred one with particles in suspension.

![Fig. 3. Height $h$ of the pulp-air interface without airflow and corresponding absolute error $\Delta h$ of the interface measurement by UTTT, plotted versus the volume fraction of particles $\phi$. The errorbars correspond to the standard deviation from temporal averaging. The small sketch right to the plot visualizes the cases. The non stirred case, where the particles are settled and the stirred one with particles in suspension.](image)

### Table 2

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<th>$m_0/\phi$</th>
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<th>2.0</th>
<th>5.0</th>
<th>10.0</th>
<th>20.0</th>
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<td>0.1</td>
<td>0.25</td>
<td>0.50</td>
<td>1.0</td>
<td>2.0</td>
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<tr>
<td>$m_0/\phi$</td>
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<td>80.0</td>
<td>100.0</td>
<td>120.0</td>
<td>140.0</td>
<td>160.0</td>
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<tr>
<td>$h_0/\text{mm}$</td>
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<td>4.0</td>
<td>5.0</td>
<td>6.0</td>
<td>7.0</td>
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### Table 1

<table>
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<th>$\rho [\text{kg/m}^3]$</th>
<th>$c [\text{m/s}]$</th>
<th>$K [\text{GPa}]$</th>
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<td>1484</td>
<td>2.2</td>
</tr>
<tr>
<td>Quartz</td>
<td>2564.1</td>
<td>6050</td>
<td>97</td>
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</table>

4. Discussion

The interface heights $h$ can be measured robustly with an uncertainty of less than $\Delta h = 0.2 \text{ mm}$. $\phi_0 = 0.25\%$ for the unstirred pulp-air case and a slightly bigger one of $\Delta h = 0.6 \text{ mm}$. $\phi_0 = 0.8\%$ for $N = 600 \text{ rpm}$ for the stirred one. This rise of the uncertainty is elicited by the complex pattern of surface waves for the stirred case. The variation in the interface height due to the particle insertion $h_{Q_0}$, which is comparable to a set point...
The error grows only slightly for the pulp-froth interface up to \( \Delta h = 0.8 \text{ mm}, r_h = 1.0\% \) for the unstirred case and \( \Delta h = 1.2 \text{ mm}, r_h = 1.5\% \) for \( N = 600 \text{ rpm} \).

Very interesting is the measured speed of sound \( c \). For the unstirred pulp, \( c \) follows the trend of the theoretical relation, whereas it stays almost constant for the stirred pulp. This leads to a maximum deviation of 1.3\% for \( c \), while the detected heights differ only about 0.3\% (cf. Fig. 3). We assume, that this particular behavior is caused by the strong stirred suspension.

It might be, that the arrangement of the transducers has influence on the measured values of \( c \). The time of flight of the reflection of the artificial target and the reflection from the interface is used to calculate the interface height (cf. Eq. (11)). Therefore it is mandatory, that the pulp composition which is passed by the ultrasound beam is identical for both on average.

The majority of the observed errors are smaller than the desired set point of \( \pm 1.0 \text{ mm} \) for lab-scale operation. In summary, UTTT can be applied to detect the level in a lab-scale flotation setup, but needs an initial calibration. In case of industrial applications the height of a flotation cell is too large for the sound pulse to travel all the way from the bottom to the interface and back. However, one could mount a small inset at about 100 mm below the expected interface position. In that way, UTTT might also be employed in the presented way to industrial scale cells.

![Fig. 4. Interface level (a) for the impeller when stopped and (b) at \( N = 600 \text{ rpm} \). No change in the average level was detectable when the rotation rate was increased (cf. green line in the pictures). However, an unsteady pattern structure of surface waves was visible on the interface at \( N = 600 \text{ rpm} \) (c).](image)

![Fig. 5. Heights \( h \) of the pulp-air interface with enabled airflow together with their absolute error \( \Delta h \) of the interface measured by UTTT plotted versus the volume fraction of particles \( \phi \).](image)

![Fig. 6. Heights \( h \) of the pulp-froth interface and corresponding absolute error \( \Delta h \) of the interface measured by UTTT plotted versus the volume fraction of particles \( \phi \).](image)

![Fig. 7. Pulp-froth interface without stirring (a) and with stirring (\( N = 600 \text{ rpm} \)) in (b). The interface was deformed additionally by the froth structure, especially in front of the baffles. This deformation did not totally subside after the impeller was stopped, due to the finite yield stress of froth.](image)

![Fig. 8. Sound velocity \( c \) for the non stirred, the stirred situation of the pulp-air case (no air flow enabled) and for the pulp-froth case plotted versus the volume fraction of particles \( \phi \). Additionally the theoretical relation for the sound velocity in a suspension (Atkinson and Kytömaa, 1992) is plotted as a solid line.](image)
5. Conclusions

This work shows that UTTT can be used to detect the height of the pulp-air and the pulp-froth interface in a flotation cell. The measured height of the interface differed from the total filling height by up to 1.0% in the case of pulp-air, and 1.5% in the case of pulp-froth. The sound velocity of the pulp was detected simultaneously to allow for precise measurement.

CRediT authorship contribution statement

T. Richter: Investigation, Methodology, Data curation, Writing - original draft. S. Heitkam: Conceptualization, Visualization, Writing - review & editing. S. Odenbach: Resources. K. Eckert: Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This project has received funding from the European Unions Horizon 2020 research and innovation program FineFuture under grant agreement No 821265.

Furthermore we would like to thank Peggy Jähningen for preparing the hydrophobic particles, Andre Kupka for measuring the size and Michael Knobel for measuring the density of the quartz particles.

References


