Fachtagung “Experimentelle Strömungsmechanik”
3. - 5. September 2024, Berlin

Laserbasierte Methoden zur Messung von Schaumhöhen

Laser-based methods for foam and froth height measurement

T. Marquardt[1,2,*], P. Naumann[2], T. Lappan[1,2], A.-E. Sommer[1,2], K. Eckert[1,2], S. Heitkam[1,2]
[1] Institut für Fluiddynamik, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Deutschland
[2] Institut für Verfahrenstechnik und Umwelttechnik, Technische Universität Dresden, Dresden, Deutschland

Lidar, Lasertriangulation, Photogrammetry, Bildanalyse, Schaumflotation
lidar, laser triangulation, photogrammetry, image analysis, froth flotation

Abstract

Online monitoring of the froth phase in flotation processes has considerable potential for optimization because its properties, such as froth height, are closely related to product quality. Since the insertion of a probe is often not feasible, measuring the froth height from above could be a simple, contactless possibility to capture the height over a large area of the froth surface. To evaluate the applicability of laser-based techniques for height measurements in foam and froth experiments, we tested a lidar sensor and laser triangulation using an industrial laser line scanner. Both techniques proved to be generally suitable for foam and froth height measurement. Investigating the measurement uncertainties, we found that the height of rising and overflowing foam is systematically underestimated. Additionally, the experiments revealed that the sensors can be used to detect changes in foam properties such as the liquid fraction or foam stability.

Introduction

Froth flotation is a process widely used in mineral processing to separate ore from gangue minerals based on their surface wettability. A suspension of finely ground ore is fed into a flotation cell. A rotor-stator unit at the bottom of the cell introduces both finely dispersed air bubbles and kinetic energy. The particles collide with the rising bubbles and the valuable particles attach to the bubbles due to their hydrophobicity. They are then concentrated in a three-phase froth, which is collected by overflowing a weir. Typically, two types of surfactants are added to the cell. Collectors are used to hydrophobize the valuable particles, while frothers are used to form small bubbles and a stable froth. Fig. 1 a) shows a schematic drawing of a mechanical flotation cell including the froth zone. The characteristics of the froth, such as its depth, are related to the flotation performance. Furthermore, the height of the overflowing froth is needed for estimating the air recovery, an essential parameter in evaluating the flotation performance. Air recovery is defined as the fraction of the air entering a cell that overflows the cell lip as unburst bubbles and is therefore an important measure of froth stability (Hadler and Cilliers, 2009).
Robust and accurate height measurement techniques are not only essential for air recovery estimation, but also for other industrial processes and laboratory-scale experiments involving two-phase foam and three-phase froth. Most processes, such as flotation, require a continuous and contactless monitoring. A simple optical measurement through the transparent side wall

of a flotation cell is only possible in certain laboratory experiments and is affected by wall effects and possible wall contamination by particles in the froth (Marquardt et al., 2024). Therefore, measuring the froth height from above could be a suitable possibility to measure the height over a larger area of the froth surface. However, depending on the application, the required measurement range is relatively large, spanning from centimeters to decimeters. Additionally, process monitoring may require a high resolution of down to 0.1 cm. Finally, foam and froth have special structural and optical properties such as opacity and a reflective surface. All of these requirements present unique challenges to the height measurement task.

To estimate air recovery, the overflowing froth height above the lip is typically measured using laser-based distance sensors such as lidar (light distance and ranging), which operate based on a time-of-flight (ToF) principle. They have already been used in laboratory-scale flotation tests (Quintanilla et al., 2021) and commercial froth monitoring systems (Aldrich et al., 2022). The optical properties of the froth surface might affect this measurement, resulting in an uncertainty in the measured height of unknown magnitude (Shean et al., 2017). In addition, lidar sensors provide only a pointwise measurement of the froth height. An alternative would be to use an industrial laser line scanner. These sensors project a line onto the surface. The height profile along this line can be calculated by triangulation. This measurement technique has already been tested for two-phase aerated gas-water systems before (Rak et al., 2017). In contrast to lidar sensors, such measurements provide height information along the projected laser line.

The aim of this work is to characterize the measurement uncertainties for a commonly used lidar sensor as well as for the novel technique of laser triangulation on foam and froth experiments. In addition, the influence of the surface properties of foam and froth is investigated. Firstly, the sensors and experimental methods used are presented, followed by the results of height measurements in two- and three-phase experiments and the evaluation of measurement uncertainties. Finally, the influence of foam and froth properties on the height measurement is discussed and the sensors are compared.

Methods and materials

Experimental setup

We tested two sensors for their ability to measure foam and froth height, a lidar sensor and an industrial laser line scanner. Both sensors also log the intensity of the measured signal. The characteristics of the sensors were investigated in preliminary tests and are summarized in Tab. 1. The lower end of the measuring range of the lidar is limited by the blind spot. If the distance to the target is less than the blind spot distance, the measured distances may be subjected to a significantly higher uncertainty than above the blind spot distance.

To determine the measurement uncertainties of the sensors, a translation stage was used (Fig. 1 b)). With this device, the distance between the sensor and the target surface can be precisely adjusted by a linear accelerator. The measurements were performed by moving the sensors down from an upper starting position. For the generation of foam and froth, two different setups were used, a foam column with a stationary foam surface (Fig. 1 c)) and a laboratory-scale flotation cell (Fig. 1 d)) with overflowing foam. The cylindrical foam column was 10 cm in diameter and 35 cm in height. Foam was generated by dispersing air through a porous frit at the bottom of the column. The air flow rate was controlled by a mass flow controller and could be varied between 0.5 and 1.5 l min^{-1}. The mechanical flotation cell had a volume of 1.8 l. The air was dispersed by a rotor-stator system. The sensors were placed above the setups and observed the froth from the top. The line scanner could be placed on the flotation cell in two directions, parallel to the weir and in flow direction.

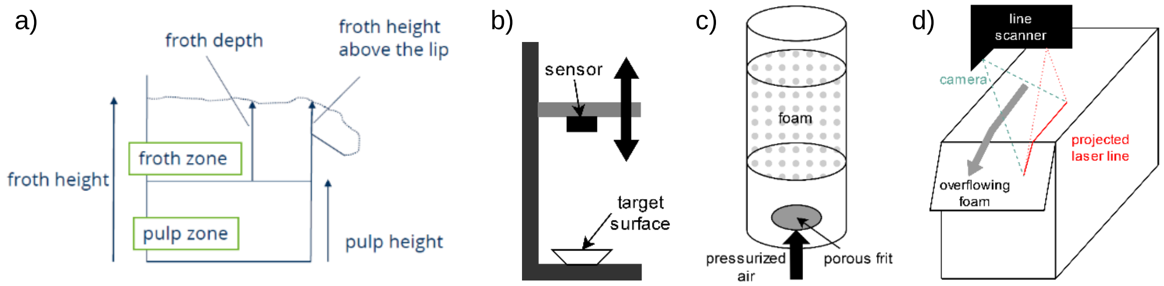

Fig. 1: a) structure of a mechanical flotation cell with the characteristic froth heights. b) translation stage. c) foam column. d) flotation cell with line scanner in flow direction.

To generate two-phase foam, sodium lauryl sulfate (SDS) with a critical micelle concentration (cmc) of 8.6 × 10^{-3} M was used (Rauniyar and Bhattarai, 2021). For two-phase foam experiments using the translation stage and the foam column, an SDS concentration of 1 cmc was used, while an overflowing foam for the flotation cell was generated with an SDS concentration of 0.05 cmc. For three-phase experiments, coal particles (20 g l^{-1}) were added to a 1 cmc SDS solution. Coal is naturally hydrophobic and therefore floatable without adding a collector. Finally, the sensors were tested for the flotation of a binary pyrite-quartz system using methyl isobutyl carbinol (MIBC, 45 g t^{-1}) as a frother and potassium amyl xanthate (PAX, 35 g t^{-1}) as a collector to hydrophobize the pyrite particles.

Tab. 1: Properties of the sensors used for foam and froth height measurement.

	Lidar sensor	Line scanner
Model	TF mini plus, Benewake (Beijing) Co., Ltd.	M2-iLAN-2 80/40, MEL Mikroelektronik GmbH
Measuring range	10 – 1200 cm	6.3 – 14.3 cm
Field of view (FoV)	(5.9 ± 0.5)° (circular FoV)	40 to 55 mm length of analyzed profile line
Measurement frequency	25 Hz	100 Hz

Data and uncertainty analysis

The lidar sensor outputs scalar distance values, while the line scanner measures a height profile. In order to obtain the height with respect to a certain zero level, a one-point calibration is required for both instruments. Precision and accuracy are used to describe the measurement uncertainty of the sensors. Accuracy or trueness Δy_m describes the deviation from the true value. It is calculated as the difference between the true distance y_{tr}, which is known by the movement of the translation stage, and the measured distance y_m. The measured distance is the arithmetic mean of five measurements. The precision $\sigma(y_m)$ describes how close the measured distances of the five repetitions are to each other and is calculated as the standard deviation of the five measurements at the same position.

Results

Measurement uncertainties for two-phase foam

For both sensors, the investigation of the precision and accuracy for two-phase foam was performed by pre-setting the distance to the foam surface with a translation stage. For the lidar, the experiment was repeated five times and compared with measurements on cardboard, which serve as an example of a diffuse reflecting surface. Fig. 2 shows the measured distances. In order to solely observe the precision and accuracy intrinsic to the sensor, no height calibration was performed. The true distance d_{tr} was determined from the known movement of the translation stage. The measured distance d_m decreases from left to right as the data is recorded for a downward movement of the sensor. The average measured distance is almost the same for the cardboard and the foam surface up to a distance of approximately 10 cm. For smaller distances, d_m is zero for the cardboard, which results in a decrease in the accuracy, Δd_m. The same can be observed for the signal intensity I_b. These results confirm that the blind spot of the sensor is at a distance of 10 cm as stated by the manufacturer. For foam, there is no sudden drop of the measured distance within the blind spot. A small fluctuation of $|\Delta d_m| \leq 1.5\ cm$ is observed at a distance of approx. 6 cm. The precision $\sigma(d_m)$ increases slightly with decreasing distances, but is less than 0.2 cm for distances greater than 10 cm. Unlike for the cardboard, there is no sudden change in the signal intensity, so no distinct blind spot can be identified. This can be explained by the different surface properties of foam and cardboard, which will be discussed in more detail later.

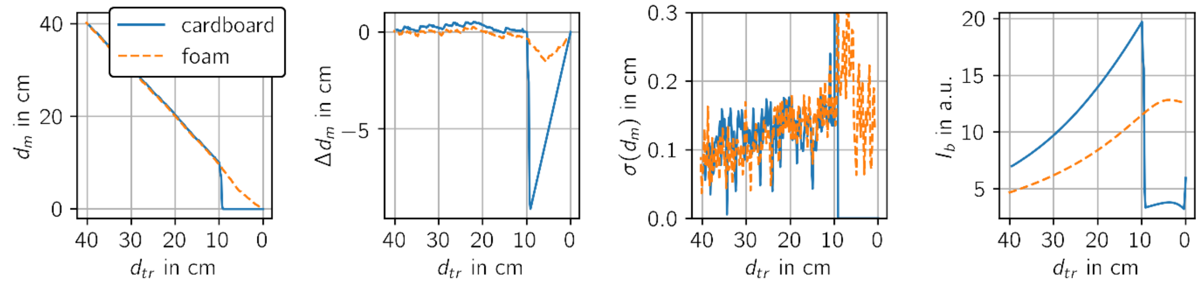

Fig. 2: Uncertainty of distance measurement using the lidar sensor on a cardboard and a foam surface. The graphs from left to right show the mean measured distance d_m of five repetitions, the accuracy Δd_m, the precision $\sigma(d_m)$ and the signal intensity I_b.

For the line scanner, data was obtained for ten positions within the entire measuring range of the sensor. As the sensor moves towards the target, the apparent height changes. At each position, the height was averaged for the five repeated measurements. Fig. 3 shows the results. For heights below 20 mm, the obtained heights were not accurate. This indicates a poor measurement performance at positions close to the foam surface. Excluding these outliers, the accuracy is within a range of 0.15 cm, and the precision is less than 0.25 cm.

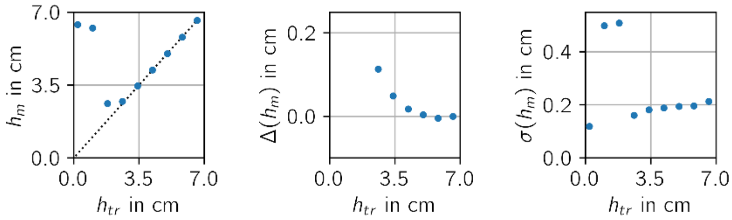

Fig. 3: Uncertainty of height measurement using the line scanner on an even foam surface. The height is averaged along the measured profile. The graphs from left to right show the mean measured height h_m of five repetitions, the accuracy Δh_m, and the precision $\sigma(h_m)$. For the accuracy, the scaling was adjusted so that the outliers are not included.

Measurement on three-phase froth

Pretests revealed that the material of the surface influences the signal intensity and, consequently, potentially the height measurement. It is therefore important to analyze this impact in order to employ the measurement techniques to flotation processes. Both sensors were examined on exemplary experiments with a three-phase foam with particles or a flotation froth. For the lidar, a rising three-phase SDS foam with coal particles was generated in the foam column. The images show a visible amount of coal in the three-phase foam. Fig. 4 presents the results of two experiments with and without particles. It is demonstrated that the height measurement worked well for both experiments. However, the signal intensity was approximately three times larger for the three-phase foam. This indicates that the addition of particles has a substantial influence on the height measurement with lidar sensors in flotation processes, which will be discussed in greater detail in a subsequent section.

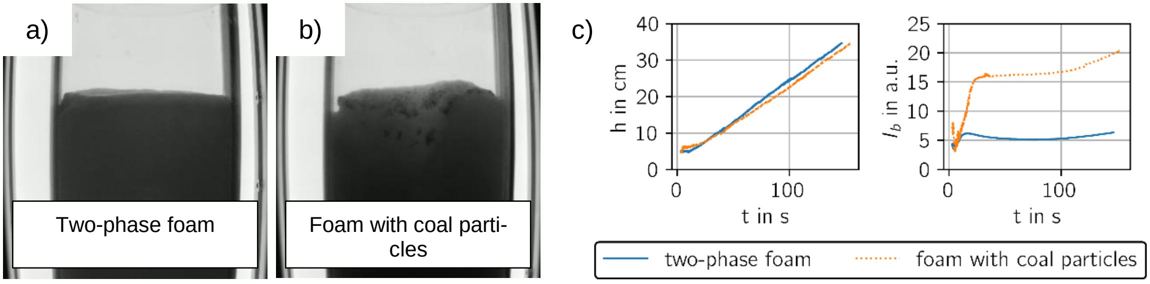

Fig. 4: Comparison of the height measurement using a lidar sensor for a two-phase SDS foam and a three-phase foam with added coal particles. a), b) appearance of the two foam samples in the 10 cm wide foam column. c) measured height h and signal intensity I_b.

The influence of particles in the froth on the line scanner measurement is demonstrated by two experiments conducted in the flotation cell, one with overflowing two-phase SDS foam and a flotation process with overflowing three-phase froth. In both experiments, the line scanner was mounted parallel to the weir. Fig. 5 presents photos of the two tests, as well as two exemplary height profiles. The images illustrate the different properties of the foam and froth surface in the two experiments. Additionally, the appearance of the projected line differs. While the line is relatively broad and light on the foam, the reflection on the froth is much more distinct. This effect is also visible in Fig. 5 c). The height profile of the froth experiment is much smoother than for the foam. Therefore, the addition of particles is advantageous for the measurement quality. Further reasons for the noisy foam height profile will be discussed in greater detail in the next section.

Fig. 5: Foam and froth height measurement in the flotation cell using the line scanner. a), b) overflowing foam and froth. c) exemplary height profile for both experiments.

Discussion

Influence of the foam and froth surface properties

Literature indicates that the properties of the foam or froth surface have a strong influence on distance measurements with lidar sensors (Shean et al., 2017). The same can be assumed for the line scanner. Therefore, this section discusses possible effects and their causes.
Most importantly, we observed an underestimation of the foam height for both sensors. Fig. 6 shows the results of an experiment with the lidar. The distance of the lidar to stable SDS foam was decreased using the translation stage. The grey area in the diagram indicates the true foam height of 2.5 – 3.0 cm measured with a ruler. The measured height was calculated using the measured distance, the calibration, and the known velocity of the translation stage. However, it is much smaller than the true height, even though there was no visible change in the macroscopic foam properties during the experiment. This effect is also reported in the literature for aerated water systems (Bizjan et al., 2024). Fig. 6 b) schematically shows diffuse or Lambertian reflectance, which is ideal for lidar sensors (Chazette et al., 2016). Fig. 6 c) shows the scattering of light within foam. Incident light is scattered in all directions within the foam, especially at the Plateau borders (Durian et al., 1991, Vera et al., 2001). This distribution of light within the foam provides an additional ToF, and thus also an underestimation of the height as well as a reduced signal intensity. The same mechanism is responsible for the reduction in blind spot distance, as illustrated in Fig. 2. The comparison of several such experiments showed that the underestimation depends on the properties of the foam such as the bubble size distribution or the liquid fraction. The influence of the liquid fraction on the lidar measurement is discussed in the next subsection.

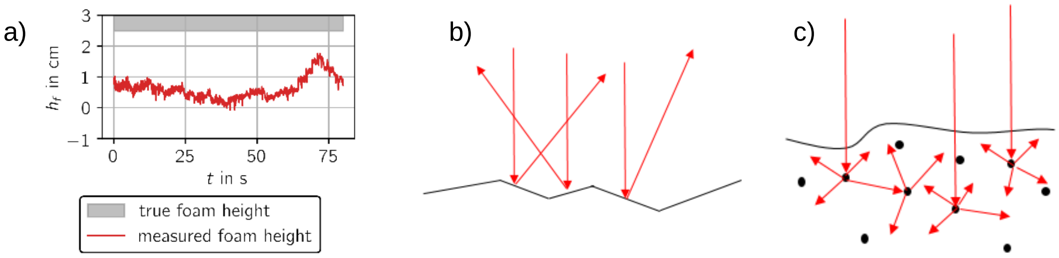

Fig. 6: Height underestimation by the lidar sensor. a) comparison of true and measured foam height. b) diffuse reflectance on a surface ideal for the lidar. c) scattering of light within the foam.

For the line scanner, experiments conducted on a planar foam surface, which was partially covered with tape, revealed an underestimation of the foam height as well. Fig. 7 presents the results. The measured height in the taped area in the left part of the plot is almost constant. The signal intensity in this area is uniform and the maximal measured value. Conversely, the height and signal intensity of the foam displayed on the right side of the plot vary considerably. The upper limit of the measured heights is identical to the height of the tape, representing the true height of the foam. At other points, the measured height is lower. The signal intensity decreases with decreasing height. This observation can again be explained by the scattering of light within the foam. Some of the incident light is scattered at the top layer of the bubbles, while another part penetrates the partly transparent foam surface. This scattering reduces the intensity of the detected light and thus the signal intensity. Similar to the lidar, the degree of underestimation depends on the foam properties. As the optical density increases, the degree of underestimation is reduced. Furthermore, the link with the signal intensity suggests whether a measuring point is located at or slightly below the foam surface. In three-phase froth, as shown in Fig. 5 b), the incident light is reflected by the particles on the froth surface and does not penetrate into the froth. A sharper height profile is obtained and the height is measured more accurately than for foam. It is therefore unlikely that froth height is systematically underestimated by the line scanner in flotation measurements.

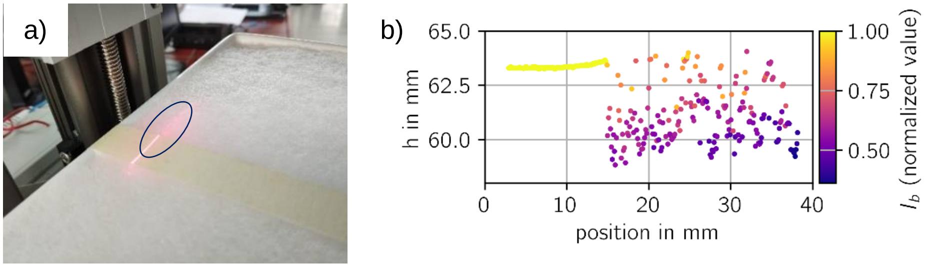

Fig. 7: Height underestimation by the line scanner. a) experimental setup. b) measured height profile h and signal intensities I_b.

Analysis of foam and froth properties

The use of lidar sensors and line scanners to measure foam and froth height can also provide insight into the properties of the foam or froth, including its liquid fraction, stability, and bubble size distribution.

As an example, the relationship between the signal intensity of the lidar measurement and the liquid fraction of foam is discussed. For a free drainage experiment, SDS foam was generated in the foam column and decayed after the air supply was stopped. Fig. 8 shows images of the foam during the decay as well as foam height and signal intensity over time. The photos show that the foam becomes more transparent during the decay phase. Due to drainage, foam coarsening occurs, as well as a reduction in the liquid fraction of the top parts of the foam. After the air supply was stopped, the measured height as well as the signal intensity decrease. The influence of the slightly decreasing foam height on the signal intensity can be neglected, since the change in the signal intensity with height is at least an order of magnitude smaller than the total change in the signal intensity observed for the experiment. Consequently, the change in liquid fraction can be correlated with the decrease in signal intensity. The liquid fraction ε of the top layer of the foam can be expressed as a function of time as $\varepsilon \propto 1/t$ (Saint-Jalmes and Langevin, 2002). The signal intensity I_b of the lidar is disproportional to the mean free path of a photon l^* for a bulk foam ($I_b \propto 1/l^*$) and a relation between the mean free path and the liquid fraction can be derived ($l^* \propto 1/\sqrt{\varepsilon}$) (Vera et al., 2001). Altogether, the decay of the signal intensity can be described using the derived time behavior ($I_b \propto 1/\sqrt{t}$). Fig. 8 d) shows an adequate agreement between this model and the measurements. For this reason, it can be assumed that the observed change in signal intensity is mostly due to the change in liquid fraction, resulting from drainage, and not due to a changing bubble size.

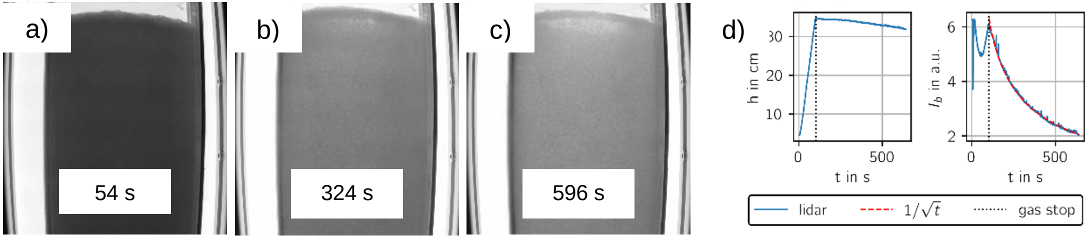

Fig. 8: Liquid fraction during foam drainage measured using a lidar sensor. a), b), c) appearance of foam during drainage in the 10 cm wide foam column. d) measured foam height h and signal intensity I_b.

Accordingly, the line scanner can be used to obtain information regarding the stability of foam and froth, for instance, during flotation processes. If the scanner is positioned parallel to the weir of a flotation cell, as shown in Fig. 5, the fluctuation of the mean height can be used as a measure for froth stability. The high temporal resolution of the used sensor is highly beneficial in this regard.

Conclusion and Outlook

Robust and accurate height measurement techniques for froth are needed to estimate air recovery in flotation processes. Both the time-of-flight based lidar sensor and an industrial laser triangulation device were found to be suitable for this task. For measurements on foam surfaces, the lidar had an accuracy of max. 1.5 cm and a precision of 0.2 cm while the line scanner had an accuracy of 0.15 cm and a precision of 0.25 cm. For both sensors, the penetration depth of the laser into the foam is a source of a systematic height underestimation. However, this effect is less pronounced for measurements on three-phase froth, which we address to the presence of particles and their influence on the froth phase in terms of its reflectance. Overall, lidar sensors are a robust technique for pointwise foam and froth height measurements in an industrial environment, while line scanners provide height measurement along a line. To yield areawise height information, image acquisition with two synchronized stereo cameras and photogrammetric reconstruction of the surface can be used, which will be investigated in future studies.

Acknowledgements

Financial support by the German Helmholtz Association in frame of the project "Securing raw materials supply through flexible and sustainable closure of material cycles" is gratefully acknowledged. This work was partially funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 431077191. We thank Lucas Pereira (HZDR/HIF), Klaus Timmel (HZDR) and Volker Waurich (TU Dresden) for their support.

References

Aldrich, C., Avelar, E., Liu, X., 2022: “Recent advances in flotation froth image analysis”, Minerals Engineering, 188, 107823
Bizjan, B., Hočevar, M., Kolbl Repinc, S., and Rak, G., 2024: “On the effect of aeration on laser ranging measurements of free water surface”, Flow Measurement and Instrumentation, 95, 102502
Chazette, P., Totems, J., Hespel, L., and Bailly, J.-S., 2016: “Principle and Physics of the LiDAR Measurement”, in Optical Remote Sensing of Land Surface, Elsevier, 201–247
Durian, D. J., Weitz, D. A., and Pine, D. J., 1991: “Multiple Light-Scattering Probes of Foam Structure and Dynamics”, Science, 252, 5006, 686 – 688
Hadler, K., Cilliers, J., 2009: “The relationship between the peak in air recovery and flotation bank performance”, Minerals Engineering, 22, 5, 451–455
Marquardt, T., Hassan, A., Jähnigen, P., Lappan, T., Pereira, L., Heitkam, S., Rudolph, M., Eckert, K. “Optical froth height measurements in a bench scale flotation test”, in preparation
Quintanilla, P., Neethling, S. J., Mesa, D., Navia, D., Brito-Parada, P. R., 2021: “A dynamic flotation model for predictive control incorporating froth physics. Part II: Model calibration and validation”, Minerals Engineering, 173, 107190
Rak, G., Hočevar, M., Steinman, F., 2017: “Measuring water surface topography using laser scanning”, Flow Measurement and Instrumentation, 56, 35 – 44.
Rauniyar, B. S. and Bhattarai, A., 2021: “Study of conductivity, contact angle and surface free energy of anionic (SDS, AOT) and cationic (CTAB) surfactants in water and isopropanol mixture”, Journal of Molecular Liquids, 323, 114 604
Saint-Jalmes, A. and Langevin, D., 2002: “Time evolution of aqueous foams: Drainage and coarsening”, Journal of Physics: Condensed Matter, 14, 40, 9397–9412
Shean, B., Hadler, K., and Cilliers, J., 2017: “A flotation control system to optimise performance using peak air recovery”, Chemical Engineering Research and Design, 117, 57–65
Vera, M. U., Saint-Jalmes, A., and Durian, D. J., 2001: “Scattering optics of foam”, Applied Optics, 40, 24, 4210