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Estimation of the bubble size and bubble loading in a flotation froth using electrical resistance tomography

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ABSTRACT

Flotation process is widely used in mineral industry for the separation of valuable minerals from low-grade ore slurry. There are several parameters such as the bubble size and bubble loading that predict the efficiency of the flotation process. These parameters can be used for the control of the flotation process. There are already some techniques that can be used for online monitoring of these parameters, for example, the high-speed video imaging and a probe sensor based on electrical resistance tomography (ERT). These methods, however, suffer for some limitations. The high speed video imaging gives information only on the surface of the froth and in the previously proposed ERT based techniques the conductivity of the froth is typically modeled to be smoothly varying. However, in reality the froth is composed of different size of bubbles having highly conductive surface and very low conductive interior which configuration cannot be modeled with smoothly varying conductivity distribution. In this paper, we propose a computational approach in which the structure of the froth is modeled and both the bubble size and the conductivity of the boundary of the bubbles are estimated. The proposed approach utilizes data measured with the standard ERT probe. The estimated bubble size and conductivity of the boundary of the bubbles are compared to online measured camera based estimates of the bubble size and bubble loading. The proposed approach is evaluated with simulated measurements and real data from Pyhäsalmi Mine. The results show that there is a high correlation between the camera based and the ERT based estimates of the bubble size. Furthermore, some of the parameters obtained from the ERT based method correlate well with the camera based estimate of the bubble loading.

1. Introduction

In mineral industry the froth flotation process is widely used for the separation of minerals from low-grade ore slurry. The grade and recovery in the flotation process depends on the structure and stability of the froth, see Neethling and Cilliers (2003), Farrokhpay (2011). The bubble size distribution, bubble loading, height of froth, liquid content of the froth, the velocity of the froth and bursting rate of the bubbles are important parameters that affect the structure and stability of the froth. There are several methods to estimate these parameters. The bubble size, the bursting rate of the bubbles and bubble loading were estimated using camera based methods in Grau and Heiskanen (2002), Kaartinen et al. (2006). The froth stability column was applied to evaluate the stability of the froth in Barbian et al. (2005, 2006). The froth stability was evaluated using electrical impedance spectroscopy in Hu et al. (2009). Simple conductivity probes, floats and pressure transducers have been used for the estimation of the height of froth, see Maldonado et al. (2008).

One possible technique for the froth flotation process monitoring is electrical resistance tomography (ERT). In electrical resistance tomography, electrodes are attached on the boundary of an object or on the measurement probe and currents are injected into the object through these electrodes. The voltages on all electrodes are measured and the conductivity of the object is reconstructed based on the measured voltages and known currents; for reviews on ERT, see Cheney et al. (1999), Kaipio et al. (2000), Borcea (2002). Note that in the literature the term electrical impedance tomography (EIT) is often used when more accuare term would be ERT.

Electrical resistance tomography has already been applied for imaging of flotation process in Cilliers et al. (1999), Kourunen et al. (2008), Normi et al. (2009), Kourunen et al. (2011),

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Lehikoinen et al. (2011), Reunanen et al. (2011). In these papers, the conductivity of the froth is typically modeled to be smoothly varying. However, in reality the froth is composed of different size of bubbles having highly conductive surface and very low conductive interior which configuration cannot be modeled with smoothly varying conductivity distribution.

The aim of this study is to estimate the bubble size and also to obtain information on the bubble loading using ERT. For this purpose, an approximative froth model is constructed and the conductivity of the boundary of the bubbles and conductivity of the slurry is estimated. The vapor inside the bubble is very low or non-conductive and the surface of the bubble can be highly conductive due to the water and mineral particles on the surface of the bubbles. Therefore it is believed that the conductivity of the boundary of the bubbles can give information on the bubble loading. In this approximative froth model, an approximative and fixed bubble size is used. Since this is not exactly correct, the so called approximation error approach is utilized. With this approach it is possible to compensate for errors caused by the unknown parameters, such as the bubble size in this study. For more details on approximation error approach applied for unknown parameters, see Kolehmainen et al. (2011), Nissinen et al. (2011b). The benefit of the approach is that it enables the estimation of the bubble size without changing the froth model during the computations.

The approximation error approach was originally proposed in Kaipio and Somersalo (2005, 2007). Since then the approach have been applied for different approximation errors and applications. The approximation error approach was applied to ERT in Kaipio and Somersalo (2005), Lehikoinen et al. (2007), Nissinen et al. (2008, 2011a), for example. In optical tomography the approach was applied in Heino and Somersalo (2004), Arridge et al. (2006), Kolehmainen et al. (2011), Tarvainen et al. (2010), for example. In electrical capacitance tomography the approximation error approach was applied in Banasiak et al. (2012). Recently, the approximation error approach was applied to seismic imaging of the aquifer dimensions in Lähivaara et al. (2014). The approach was recently applied to atmospheric modeling in Lipponen et al. (2013a).

In this study, the proposed method is evaluated with simulated measurements and also with real measurements conducted at Inmet Pyhäsalmi Mine at Pyhäsalmi Finland. The real measurements were obtained using the Outotec LevelSense™ sensor. It has been found earlier that this sensor can be used to control and optimize the flotation process, see Lehikoinen et al. (2011), Vauhkonen et al. (2013). The ERT based estimates of the bubble size and conductivity of the boundary of the bubbles are compared to camera based estimates of the bubble size and bubble loading. Furthermore, the average conductivity of the froth is obtained from Outotec LevelSense™ sensor and it is used as a reference parameter.

The rest of this paper is organized as follows. In Section 2, a brief preview of the Outotec LevelSense™ sensor and measurement system is given. Furthermore, the approximative model for the conductivity is explained and the measurement model is represented. In Section 3, the Bayesian formulation of the ERT problem is reviewed and the estimation of the conductivity and bubble size is explained. The details of the computations (parameters and used methods) and the reference estimates are explained in Section 4. The proposed approach is evaluated using simulated and real data in Section 5 and the conclusions are given in Section 6.

2. Materials and methods

2.1. Measurement probe

In ERT, electrodes are typically attached on the surface of the object and the measurements are conducted using these electrodes. This measurement arrangement is used when relative small objects such as flow pipes and small measurement tanks are investigated. The size of the flotation cell is typically so large that the measurement devise that measures on the boundary of the cell would be impractical and expensive to construct. Therefore, a probe sensor where the electrodes are on the surface of the probe is used for the monitoring on flotation process.

In this study, the real measurements were carried out using Outotec LevelSense™ sensor. In this sensor $N_{\mathrm{el}} = 22$ ring shaped electrodes are attached on the boundary of the measurement probe. The height of the electrodes is 1 cm and the space between the electrodes is 2 cm. The radius of the measurement probe is 3 cm. The arrangement of the sensor in the flotation cell and a picture of the sensor in the flotation cell at Pyhäsalmi mine are shown in Fig. 1. Using the electrodes, electric currents are injected into the domain and corresponding voltages V are measured using the same electrodes. The currents are injected between all adjacent pairs of electrodes and the voltages are measured between all adjacent pairs for all current injections. The measured voltages are collected to one measurement vector $V \in \mathbb{R}^{441}$. The amplitude of the injected current is 13 mA. The conductivity distribution σ around the probe can be estimated based on the known currents and measured voltages.

In Outotec LevelSense™ sensor, several parameters are computed using the measurements. These parameters include the conductivity of the froth (bulk conductivity), the height of the froth, the place of the froth/slurry interface and conductivity of the slurry, for example. These parameters are used in the control of the flotation process. For more detailed information on the Outotec LevelSense™ sensor and controlling of the flotation process, see Lehikoinen et al. (2011), Vauhkonen et al. (2013).

2.2. Modeling of the conductivity

The conventional approach in ERT is to model the conductivity to be smoothly varying. However, in reality the froth is composed of different size of bubbles having highly conductive surface and very low conductive interior which configuration cannot be modeled with smoothly varying conductivity distribution. In this work, the structure of the froth is modeled in the finite element model in order to estimate both bubble size and conductivity of the boundary of the bubbles.

A schematic image of the computation domain is shown in Fig. 2. The ring shaped electrodes are shown on the boundary of the probe. When ring shaped electrodes are used, the measurements are averaged in the angular direction. The angular position of the inhomogeneity cannot be reconstructed with these measurements. A reasonable approximation with this type of application and measurement configuration is that the conductivity is invariant in the angular direction. Recently, a 2D cylindrically symmetric forward model for probe geometry in ERT was proposed in Nissinen et al. (2013). This model is accurate model as far as the conductivity is rotationally invariant. In Nissinen et al. (2013) it was shown that with asymmetric targets the estimated conductivity using cylindrically symmetric model is close to the angular average of the asymmetric 3D conductivity. The cylindrically symmetric forward model is used also in this work. The solution of the forward problem is computed using finite element method (FEM). One major benefit of the cylindrically symmetric forward model is that the construction of the 2D model for the froth is much easier than full 3D model. Furthermore, the cylindrically symmetric forward model is computationally faster than full 3D model.

The computation domain $\Omega \subset \mathbb{R}^2$ is divided to three separate regions. These regions are the boundaries Ω_{b} of the bubbles in the froth, air Ω_{a} inside the bubbles and slurry Ω_{s}. The bubbles are modeled to be squares and the length of the edge of the square