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Application of ECT to solid concentration measurements during granular flow in a rectangular model silo

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ABSTRACT

The paper presents results of concentration changes in cohesionless sand during dynamic mass flow in a rectangular model silo composed of a bin and hopper. Electrical capacitance tomography (ECT) was used. Sensors were located outside the silo along both the periphery and height. Local horizontal one-dimensional and cross-sectional two-dimensional evolutions of solid concentrations in dry sand during silo discharge were determined. The first ones were estimated from the raw data and the latter were obtained with the aid of the reconstructed data using a Linear Back Projection algorithm (LBP) to solve an inverse problem. Experiments in a model silo were carried out with two different initial sand densities and wall roughness grades. The measured results with ECT were compared with corresponding ones obtained with a Particle Image Velocimetry (PIV) method.

Keywords: Density; Granular material; Electrical capacitance tomography; Particle Image Velocimetry; Rectangular silo; Silo flow; Solid concentration; Wall roughness

1. Introduction

Electrical capacitance tomography (ECT) is the most powerful tool among available tomographic techniques due to its high-speed capability, low construction cost, high safety and suitability for small or large vessels (Williams and Beck, 1995; McKee et al., 1995; Plaskowski et al., 1995). ECT is used to obtain information about the spatial distribution of a mixture of dielectric materials inside an insulating vessel by measuring electrical capacitances between sets of electrodes placed around its periphery and converting them into an image showing the distribution of permittivity (Byars, 2001; Lionheart, 2001; Yang and Peng, 2003). It takes into account the fact that concentration changes in materials are proportional to the variation of dielectric permittivity. ECT can be used with non-conducting materials such as plastics, hydrocarbons, sand or glass. Tomography technique is non-invasive (it does not require a direct contact between the sensor and object or domain of interest) and is non-intrusive (it does not disturb the nature of objects being explored). ECT was first developed in early 1980s for process imaging, and it has since been applied to imaging gas/solid, and gas/liquid and more recently, gas/liquid/solid flow (Dyakowski et al., 1997; Plaskowski et al., 1995; Yang and Liu, 2003; Marashdeh, 2006). It is usually used for cylindrical vessels (therefore, ECT systems mainly apply circular sensors). The most important applications are in the oil industry, such as oil and gas separation. Measurements analyzed offline can be used to estimate process efficiencies, to identify flow problems (Tejchman and Gudehus, 2000) and to validate computational flow models (Wojcik and Tejchman, 2009).

The intention of the paper is to check the capability of ECT to visualize solid concentrations during dynamic granular flow in a rectangular model silo. The results of concentration changes in cohesionlesss sand during silo flow were presented as one-dimensional horizontal plots and two-dimensional images in time on the basis of both the raw and reconstructed data, respectively. Smooth and very rough walls were used in the silo. Sand was initially dense or initially loose. The ECT system used was constructed by the Warsaw University of Technology (Brzeski et al., 2003). The measurements were performed at 3 different levels along both bin (using

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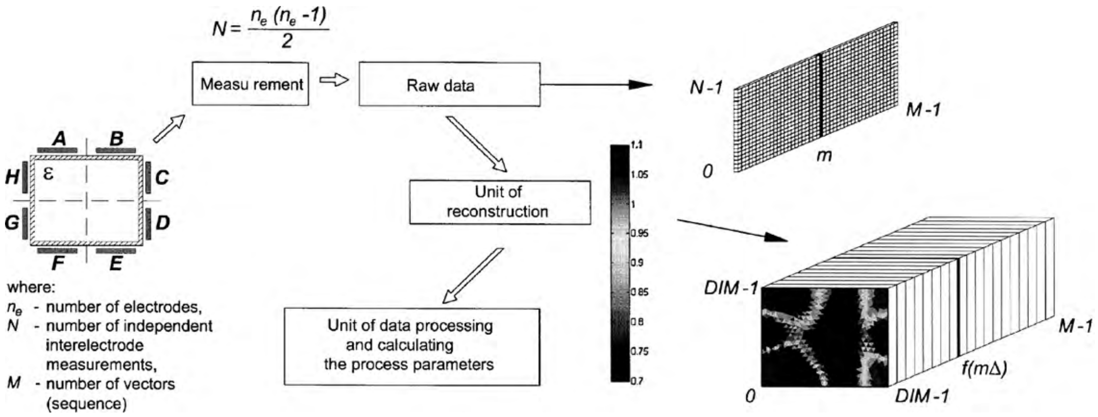

Fig. 1 – Concept of tomographic measurements and data processing.

rectangular electrodes) and hopper walls (using triangular electrodes).

The innovative points concern the measurements of sand concentration in a rectangular model silo during silo discharge. The research concerning this specific area has been carried out for the first time. The ECT method has already been successfully applied by authors to measure solid concentration changes in cohesionless sand during gravitational granular flow in a model silo with a cylindrical cross-section (Niedostatkiewicz et al., 2009). The method was useful to determine a diameter of core flow (Niedostatkiewicz et al., 2009) and a location of strong dynamic effects in the interior of the moving solid (Wilde et al., 2009). The ECT sensors have also been applied in rectangular containers by other researchers (e.g. Yang and Liu, 1999; Wang et al., 2003; Yossontikul et al., 2002; Rerkratn et al., 2006), but they have been used to measure solid concentration changes in materials significantly different than sand (e.g. polymer granulate, vegetable oil with a teflon stick) and during static problems. The measurements of the solid concentration in the one-phase material like sand are obviously more complex by means of ECT due to a low difference in permitivitty between sand and air.

In the paper, the ECT results were qualitatively compared with the corresponding ones obtained with a Particle Image Velocimetry (PIV) method and with an ECT method in a cylindrical model silo (Niedostatkiewicz et al., 2009).

2. Procedures applied in ECT

The sensor hardware in ECT is composed of a number of electrodes surrounding the wall of the process vessel. The entire procedure of our measurements during silo flow using ECT can be summarized in five steps (Niedostatkiewicz et al., 2009), Fig. 1:

(1) Calibration: measurements of capacitances between each pair of electrodes were conducted with a material of low electrical permittivity (air) and a material of high permittivity (sand). All subsequent capacitance values were normalized to have values between zero (when the sensor was filled with the lower permittivity material) and 1 (when it was filled with the higher permittivity material).
(2) Direct measurement of the capacitance between each pair of electrodes (so-called raw data): independent capacitances between electrodes were measured for each single time point. A sequence of frames collected in time created the measurement raw data.
(3) Sensitivity matrix calculation: the information about the influence of the permittivity distribution in sand on measured capacitances (between any pairs of electrodes) was stored in the so-called sensitivity matrix, which contained the impacts of dielectric constant changes in pixels of the image on changes of capacitances (changes of the mixture of air and sand). The sensitivity denotes a linearization of the capacitance response for a perturbation of the physical property inside the imaging domain (it can be considered as a possibility to detect a small change in the material permittivity). The sensitivity matrix was calculated by solving the Poisson's equation for the electrical field (by using the finite element method).
(4) Solution of the so-called forward problem for the iterative image reconstruction algorithm: this step was carried out during the iterative image reconstruction procedure. The capacitance was calculated for a given permittivity distribution inside the sensor space and boundary conditions. The solution of the forward problem enabled one to determine the difference between the measured and calculated capacitances in each step in order to minimize the error in the reconstruction image.
(5) Solution of the inverse problem for the image reconstruction: an inverse problem denotes a process of estimating the permittivity distribution from the measured capacitance data. A Linear Back Projection (LBP) algorithm was used for approximating the dielectric distribution in cross-sectional image. LBP is a simple image reconstruction algorithm and has commonly been used in ECT for the image reconstruction (to save the calculation time) but is also not very accurate. In LBP, the capacitance was assumed to be formed from a superposition collection of different high permittivity pixels, and it was written as a function of the sensitivity matrix. It is very fast since it requires only a multiplication of the sensitivity matrix times the capacitance vector to obtain the solid concentration. The results were normalized based on the response of the sensor filled with a high and low permittivity material.

3. Experimental silo set-up

Laboratory tests were carried out with a rectangular perspex model silo consisting of a bin and hopper during a dynamic mass flow (Fig. 2). The height of the model silo was $h = 0.34$ m, the width $b = 0.09$ m and the depth $d = 0.07$ m. The wall thickness was 5 mm.