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Study of granular flow in silo based on electrical capacitance tomography and optical imaging

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A B S T R A C T

This paper presents a comparison between optical images and two different modalities of electrical capacitance tomography (ECT), namely an off-the-shelf ECT system and a model one combining an inductance (L) - capacitance (C) - resistance (R) meter with a multiplexer. This comparison was performed to analyse the degree of measurement accuracy and to estimate the spatial resolution of the ECT systems. In this case, the detection of the position of flow boundaries during silo discharging and its translation when discharging changes from concentric to eccentric were investigated. A versatile rectangular silo model was used to generate different types of funnel flow of rice material, which was designated as the most adapted granular material to create both optical and electrical permittivity contrasts between stagnant and flowing zones. When a high temporal resolution is not requested, the model ECT system reduces the measurement error of flow boundary detection between 3% and 9% when compared with optical measurements. Moreover, the system is able to capture boundary translation of about 5% of the silo bin width, which is below the assumed spatial resolution of standard commercial ECT systems.

1. Introduction

Storage solutions like hoppers or silos have major use in a various range of industrial applications, such as agriculture, pharmaceutical industry or even in nuclear engineering (pebble bed reactor). Their purpose is two-fold: to store materials – usually granular materials – and to discharge them with a controlled speed for further usage (e.g. drug dosage, power generation). The geometry of the structure and the initial packing of the granular materials have strong effects on the type of flow (e.g. mass flow, semi-mass flow of funnel flow) and on the discharging rate [1,2]. Moreover, silos with asymmetric design or inclined walls have also been designed for discharging set-up efficiency, leading to so-called eccentric discharging. It is known that such a flow type generates strong normal pressure at the silo wall that can have a direct impact on the structure integrity during servicing [3–5]. Therefore, the biggest challenge for researchers and engineers is to define the best silo design that meets with flow specifications for given granular material and application. This has often induced the development of solid numerical simulations, usually based on discrete element method (DEM) [6–8] or finite element methods (FEM) [9–11] that can predict the structure and behavior of the silo during exploitation. Moreover, measurement techniques have also been adapted to monitor online material behavior during filling, storing and emptying processes.

As far as experimental measurement is concerned, recent studies involving tomography technology take into consideration two different modalities: X-ray tomography and electrical capacitance tomography (ECT). While the former have shown its potential to quantitatively characterize structural changes occurring during mass and funnel flows [12–14] due to its high spatial resolution capabilities, the latter one has shown its usefulness in investigating rapid changes revealed during dynamic phenomena such as shear zone presence during mass flow [13,15,16] due to its good temporal resolution. In recent years, the technique has shown its usefulness to investigate industrial processes such as moisture ingress in cement-based materials, fluidized beds, liquid/gas separation or chemical process conveyors [17–20], with the upstream usage of 3D ECT sensor layouts [18,19,21,22], and downstream usage of advanced data processing strategies for flow identification and monitoring [21,23–25]. However, its main drawback, which is a spatial resolution limitation due to the non-linear nature of the electrical field and the reduced number of measurements imposed by the limited number of electrodes, reduces significantly its appealing tomography nature and development beyond Technology Readiness Level TRL 6–7 (demonstration in high-fidelity lab / operational environment). There has been a growing consideration to avoid the image reconstruction step (which is time consuming if based on complex non-linear mathematical approaches and may lead to images that are prone

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to interpretation issues) and focuses only on analyzing raw signals to study dynamic processes, as mentioned in [25–27]. However, in the current study, since the gravitational process can be controlled without losing its important dynamic characteristics such as concentration changes between stagnant and flowing zones during funnel flow, it was decided to evaluate the level of accuracy of ECT image reconstruction to determine flowing zone boundaries and its evolution with respect to the hopper configuration (i.e. symmetric/asymmetric setting).

In order to investigate the influence of the hopper parameters mentioned above, authors have realized the need of designing a versatile experimental silo system that enables to control key parameters such as outlet width, hopper angle and orientation of bin part. In such matter, changes from concentric funnel flow to eccentric mass flow or avalanche-like flow can be possible. Such silo design as well as preliminary results of concentration changes in concentric/eccentric funnel flow measured using ECT have already been presented in [28]. Particularly, a good imaging contrast was found between so-called stagnant and flowing zones. However, the study has revealed some doubts concerning the interpretation of the results that may be related to either ECT measurements carried out with a LCR meter or experimental conditions linked with the silo discharging process. Therefore, new experimental consideration has been thought to better conclude about the discharging processes based on ECT data. The main aim of the paper is to compare the results recorded simultaneously between the ECT systems and a digital camera, the latter being considered here as a reference measurement system since it is frequently used for gravitational flow experiments in the case of rectangular cross-sectioned systems [29–31]. This comparison allows to identify the capability of ECT systems to capture changes at the level of flow boundaries related to silo settings, especially the positioning of the outlet and hopper angles mentioned above.

The structure of the paper is the following. Firstly, experimental setup is presented, which highlights the experimental silo stand as well as the measurement techniques. Secondly, the experimental results section presents and discusses the comparison between the quantitative results gathered by a digital camera and the ECT systems to attest the level of accuracy of the latter technique for the detection of the stagnant zone boundaries. In that matter, tests have been carried out for concentric and eccentric funnel flow regimes in order to see if ECT measurements can detect the difference of stagnant zone localization for these different flowing setups. The paper ends with the conclusion and perspectives of work.

2. Materials

2.1. Experimental stand

The main view of the experimental silo stand is shown in Fig. 1a. Firstly, one can see the versatile silo that was designed for the purpose of the paper (detailed view on Fig. 1b). The inner rectangular cross section of the bin is of size $W_b = 24$ cm (width) by $B_b = 15$ cm (breadth). The structure is made of 0.5 cm thick polystyrene sheet. One can see on Fig. 1b that the positioning and angle control of the oblique hopper sheets are managed by means of two metallic rods on each side. Moreover, both parts can slide to control the outlet width, in order to adapt to the mean grain size of the granular bed and control the discharge velocity. The front and back sheets of the bin are longer than the side sheets and are inserted in slits so as the whole structure can adapt to the different heights of the silo when the hopper angle is changed from funnel flow to mass flow set-ups. In any case, the bin height H_b is 35 cm. With such a device, a wide range of discharging modes can be studied, from concentric funnel flow to eccentric mass flow. This is simply achieved by: (1) translating the outlet horizontally left to right, keeping its width constant, (2) changing the angle of the left hopper sheet to a given value, (3) translating vertically the silo bin to be in contact with the left hopper sheet and (4) changing the angle of the right hopper sheet to a given value to be in contact with the right edge of the silo bin.

One plane of 12 electrodes was fixed on the outside of the bin part of the silo, 2 cm above the bin-hopper boundary (Fig. 1c-d). The electrodes were made of copper adhesive and of size 5.5 cm by 6.5 cm on the front and back sizes and 7.25 cm by 6.5 cm on the side, leaving in both cases an electrode interspace of 0.5 cm. In order to reduce electrical noise, the electrodes were surrounded by ring and flat radial guards electrodes, all connected to the ground. Moreover, electrodes were connected to the bottom ring guard electrode with insulation resistance of 1 MΩ to avoid electric charge build-up on the capacitance electrodes during discharging experiments.

The electrodes were connected sequentially to two different electrical tomography setups, which are shown in Fig. 1a:

- Commercial ECT system from ECT instruments Ltd.
- Agilent E4980A Precision LCR meter[1] connected to home-made multiplexer to simulate real capacitance tomography system, named hereinafter referred to as the model ECT system.

The first system follows a traditional ECT design based on AC-based capacitance measuring circuit with high-frequency sinusoidal excitation and phase-sensitive demodulation [32]. This circuit can measure the change in capacitance as small as 0.0001 pF and it can acquire image data at 140 frames per second from a 12-electrode sensor. In the present case, measurements were acquired at a frequency of 60 Hz.

The second system that couples a multiplexer with a LCR meter was intended to reconstruct permittivity maps based on real capacitance measurements. The multiplexer is based on the Arduino® technology. However, because of the time needed to switch between pairs of electrodes in the multiplexer this model ECT system cannot work in real-time mode. This implies that the investigated process is stopped, which hinders the use of the model ECT system for many dynamic applications, such as plug/slug flow or fluidized beds. The system integrates 5 ms between two consecutive measurements for stabilisation issues. Moreover, in the case under consideration, averaging of three measurements was done for each electrode pair. However, in the case of gravitational flow in silo, the process can be stopped without creating strong concentration changes. It can be possible to increase measurement acquisition speed of LCR meter at the expense of reducing the measurement accuracy. In this investigation the LCR meter was used as the reference tool, so the accuracy of the measurements was more important than the acquisition speed.

Last but not least, ECT-based results are compared with the ones obtained from Basler acA2040-180kc colour camera with the CMOSIS CMV4000 CMOS (Complementary Metal-Oxide Semiconductor) sensor that has the size of 11.3 mm × 11.3 mm (pixel size 5.5 µm × 5.5 µm) and an array size of 2046 × 2046 pixels. A slow acquisition rate of 2 frames/s was chosen to better emphasize concentration changes and facilitate flow boundary detection, which will be explained in Section 3.2

2.2. Studied material

At the beginning of this work, no particular material was targeted. Previous ECT studies used polystyrene pellets (PP) or quartz sand to investigate solids flow in pneumatic conveyors or silos [15,16,33,34]. Both present adapted electrical properties for ECT investigation, i.e. low dielectric constant. However, other materials were also considered for this study, mainly driven by size considerations. Indeed, while PP is relatively large in size (7–8 mm average diameter), quartz sand is small ($d_{50} = 0.8$ mm) and difficult to handle with current versatile silo design.

[1] An electronic equipment that measures inductance (L), capacitance (C) and resistance (R) of an electronic component.