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Experimental Capacitance Planar Array Sensor Design for Flow Monitoring in Fluidized Bed

1. Introduction

Monitoring and proper control of multiphase flows in fluidized bed are crucial for process efficiency and safety. Since these types of processes can be found in a wide range of industrial applications, including chemical reactors [3], researchers are trying to develop techniques, which can be applied to investigate multiphase flows for many years. However, it is not possible to develop an universal sensor for every scenario and existing measurement or visualization methods are more or less suited, depending on the type of processes, materials and requirements for spatial and temporal resolution. The most commonly used tomographic methods work noninvasively, but have many limitations. For example, electrical resistance or capacitance tomography [14] suffer from lack of spatial resolution, whereas tomography methods based on ionizing radiation, such as gamma ray tomography [6], or X-ray tomography [1], are expensive and are often quite slow. On the other hand, a sensor principle named wire-mesh sensor [4], which employs a wire electrode grid in the cross section to measure electrical conductivity or permittivity, can give about 2 mm of spatial and 10 kHz of temporal resolution, but is invasive.

Another sensors based on direct imaging are planar array sensors. They employs an array of electrodes which may have different geometries, such as interdigital structures [8]. The operation principle is based on the interaction of an electrical field with the material under test. The perturbation of the electrical field is a measure of the materials' electrical properties. The interdigital sensors have been already used in a diversity of applications, such as telecommunications, microelectromechanical systems, nondestructive testing, piezoacoustics and biotechnology as well as in chemical and physical sensing [7, 9 ,11].

The proper design of the capacitance planar array sensor is particular for a concrete application, whereas more or less the same measuring electronics can be used with the

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different sensors. The reason for that is the fact that the sensor design determines the system capabilities from which the most important are spatial resolution and depth sensitivity. In this paper we focused on gas-solid flow, which occurs in fluidized beds.

In a fluidized bed a solid particles bed is being fluidized with a gas. Inside it, nearly solids-free bubbles or clusters of a higher concentrated disperse phase can be observed depending on the operation parameters, from which the highest influence has a fluidization velocity [12]. The structure of this flow has an important influence on heat and mass transfer and as a result on the reactor performance. Hence, to enable the possibility to control these processes, vertical and horizontal distributions of solids and gases inside the reactors should be measured. To allow a visualization of the flow structures we inserted a planar array sensor inside an experimental fluidized bed column tolerating some intrusiveness of this solution.

2. Sensor design

The planar array sensor was manufactured using common printed-circuit board (PCB) fabrication technology. It is simple and low-cost technology, which permits a rapid design and manufacturing of almost unrestricted sensor geometries, which may be required for other process applications.

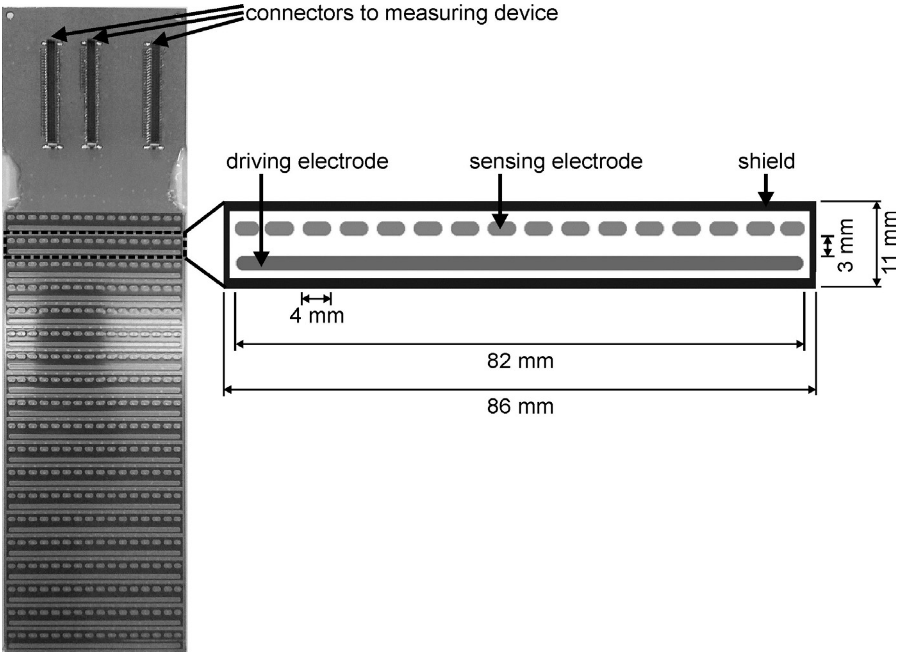

Fig. 1. Part of a planar array sensor and in detail the geometry of one block with electrodes

The developed sensor board includes six layers of copper electrically isolated from each other and glued together. The first layer includes sensing and driving electrodes, as well as grounded shielding. Third and fifth layer was used to connect electrodes by vias (holes between layers of PCB used to connect paths) to the three high-density connectors located at the top of the sensor. These connectors allow the sensor to be attached to the measurement data collection apparatus. The rest of layers (2, 4, 6) compose of grounded shields. The whole sensor contains 1024 sensing points organized in 64 blocks. Each block consists of 1 independent transmitter electrode and 16 receiver electrodes, which are connected along all the blocks. The size of entire sensing area is 86 mm by 706 mm. Figure 1 depicts the part of the sensor with connectors and in detail one block with transmitter and receivers.

3. Measurement apparatus

The measuring device used to operate the sensors is based on a capacitance wire-mesh sensor electronics [5] and is described in details in [10].

In order to measure the capacitance of the sensing structures the AC-based capacitance measuring method [13] with logarithmic detection and demodulation of the AC signal was employed [4]. The electrical displacement current flowing from the transmitter electrode to the receiver electrode is converted to an AC voltage V, which amplitude is proportional to the capacitance C of a sensing structure (Eq. (1)):

$$V = a\ln(C) + b \tag{1}$$

where a and b are circuit constants which are determined experimentally. The capacitance measured at each sensing structure is directly proportional to the relative electric permittivity of the substance over it in the form (Eq. (2)):

$$C = \varepsilon_0 \varepsilon_r k_g \tag{2}$$

where ε_0 = 8.85 pF/m is the permittivity in vacuum and k_g is the geometry factor determined by the sensing structure. To obtain a matrix representing the permittivity distribution over the whole sensor, the device is scanning all sensing points. Values, which are measured, are stored into the RAM module of a data logger integrated with the measuring device. In order to analyze and visualize measurements, the data is transmitted from the data logger to a computer through a USB interface, where the dedicated software is processing it.

This technique does not require image reconstruction, but the calibration and data normalization is still needed. In this work we perform the normalization according to a parallel capacitor model [2].

4. Experiments

Fluidized bed test facilities contain a column of 90 mm internal diameter and a height of 1 m. The column was made from Plexiglas. From the bottom, it was closed with an air distributor, which was connected to an air compressor. Inside the column the capacitance planar array sensor board was placed in a middle of the column diameter. The setup schematic is outlined in Figure 2.

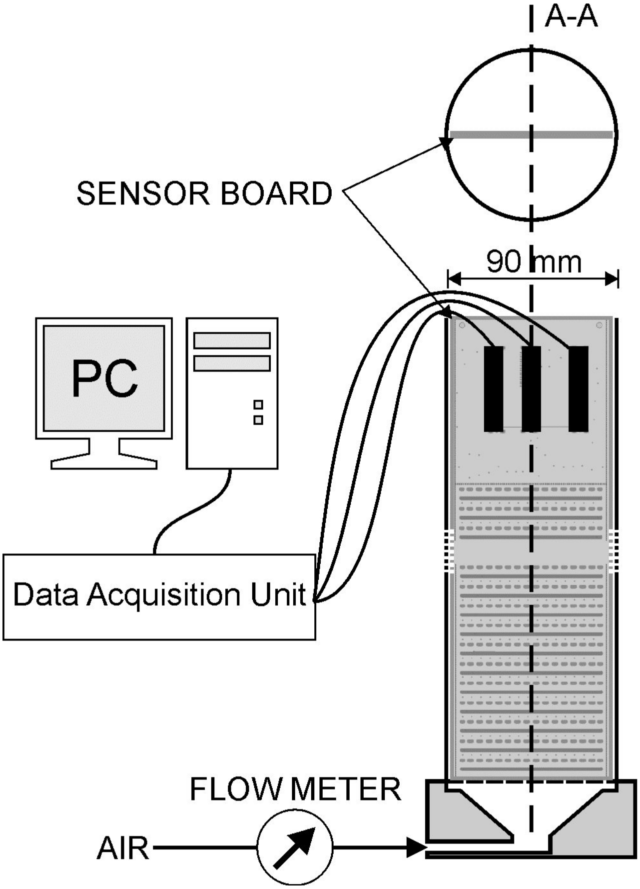

Fig. 2. Experimental setup for fluidized bed

As a bed we used commercial porous α-Al_2O_3 catalyst spheres (Duranit® D99). Relative electric permittivity for the pure Al_2O_3 is 9.33. However, for the porous particles the bulk permittivity value is accordingly lower and was measured to be between 2.1 and 2.6. The average diameter of the bed particles was 3.5 mm and the bulk density was approximately 2100 $kg\cdot m^{-3}$. All the experiments were performed in ambient room temperature, air pressure of 0.3 MPa and a flow rate of 14 000 l/h.

As a reference for minimum and maximum values for normalization procedure, we scanned column first empty and secondly fulfilled with the bed spheres, before running the experiments. During the experiments, we were acquiring 1000 frames per second and after that, we applied a moving-averaged filter over 20 frames, what matches 20 ms. Furthermore, to improve image quality we applied cubic interpolation from the original 64×16 to a 128×32 pixels.

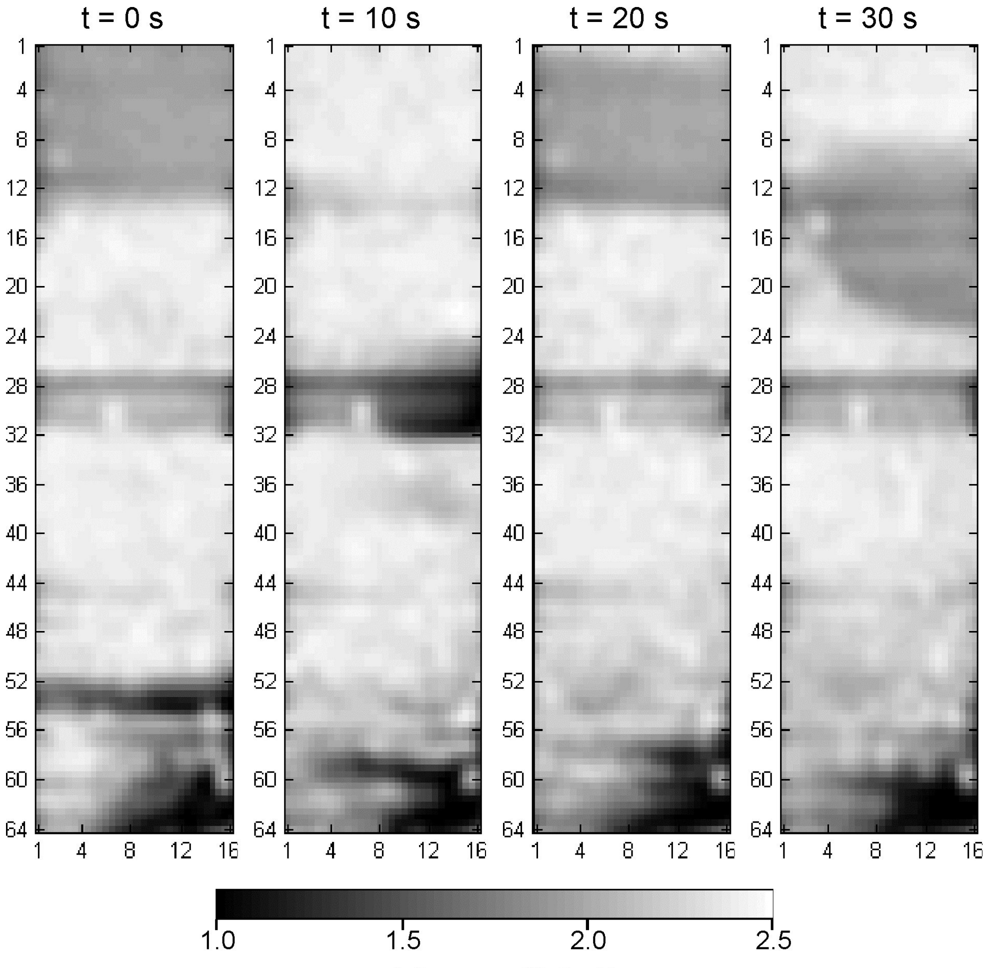

Fig. 3. Exemplary images gained with a capacitance planar array sensor during a bed fluidization

Figure 3 reveals the exemplary images from the bed fluidizations. It can be noticed that due to the large amount of sensing points we are able to observe shapes of a bigger air bubbles and concentration regions of a smaller ones. Because the sensor is long enough to cover the whole height of a column, the conditions in the entire column can be monitored including the air bubbles flow direction. Nevertheless, there are some parts of the sensor which does not react properly, e.g. in the right bottom corner of the sensor. This might be a result of the extensive sensor length. It is so long that the capacitance values measured at the top of the sensor board can vary a lot from the capacitance values, which can be measured at the bottom. In effect sensitivity of these sensing points is much different. To reduce this effect, the connectors on the board should be located closer to the electrodes and the disparity of paths lengths should be avoided. The problems with the proper sensing can also be observed along the diagonal where the vias on the sensor board are located. Another problem consists in measurements used as the minimum and maximum values for normalization. Since the packing level of a bed, during the calibration and experiments, can be slightly different, we noticed that performing normalization with the data coming only from the calibration introduces some error in the images. As a result, we decided to perform the dynamical normalization with the data from the experiments. Thus some other calibration methods should also be considered in the future.

5. Sensitivity analysis

In order to analyze the sensor's depth sensitivity we prepared a computer model of one sensor block and performed the electrical field simulations using COMSOL Multiphysics software. We put a virtual test object, which was a 3 mm wall length cube, over the sensor model like it is shown in Figure 4.

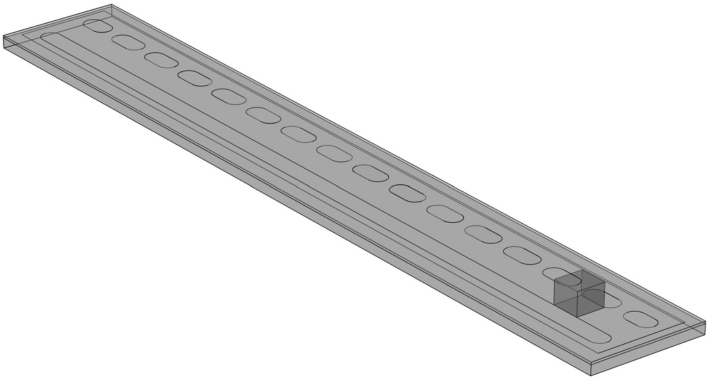

Fig. 4. A planar array capacitance sensor model with a virtual cubic test object

Electrical permittivity of the test object and a distance from the sensor was variable, while the surrounding media was assumed to be gas ($\varepsilon_r = 1$). For each setting, we calculated the capacitance between one pair of transmitter and receiver electrodes. The graph showing the results of the simulation is presented on Figure 5. As it can be noticed on this graph, for objects, which stick to the sensor the ratio between capa-citance and relative permittivity, is almost linear, and for objects that are distant from the sensor not more than 2 mm we can assume that this relation is also linear but only for relative permittivity below about 10. However, for more distant objects (more than 2 mm from the sensor), there is almost no response for permittivity changes what limits the sensor depth sensitivity.

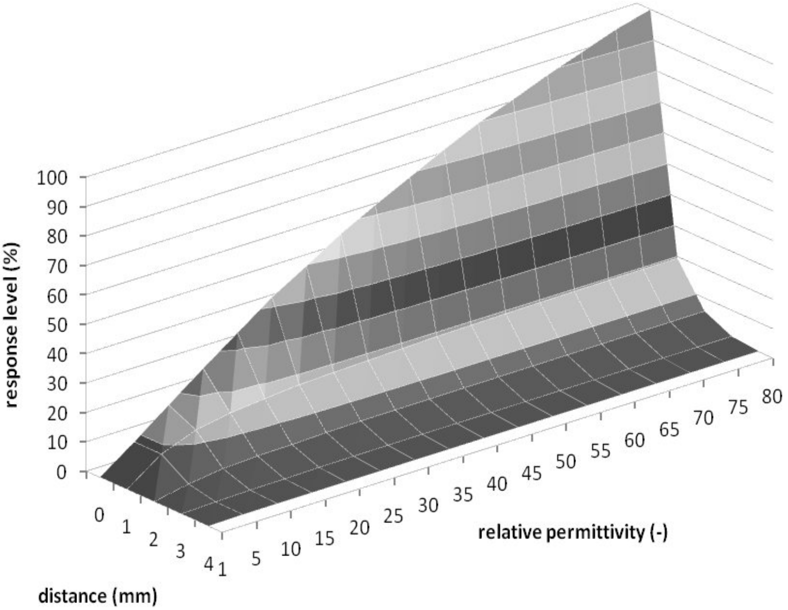

Fig. 5. Simulated response of one electrodes pair of a capacitance planar array sensor as a function of relative permittivity and distance of a test object from a sensor board

6. Conclusions

The planar array sensor have been designed and mounted inside the column of the experimental fluidized bed facility to visualize the bed distribution during the fluidization. The evaluation of this system shows that it might be a very useful method for this kind of processes. The particular advantage is feasibility to produce an overview of a whole process along a process vessel. However, the sensor is invasive and some design aspects still need to be changed. The drawback of this system is imaging only close to sensor, since the depth sensitivity, as we determined numerically, is in the range of a few millimeters.

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