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AN ELECTRICAL CAPACITANCE TOMOGRAPHY STUDY OF PRESSURIZED FLUIDIZED BEDS

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ABSTRACT
Simultaneous electrical capacitance tomography measurements for two planes were performed to obtain detailed information on bubble characteristics in a pressurized fluidized bed. Average permittivity values were used to get estimates of bubble sizes, while cross correlation was applied to the signals of both planes to obtain average bubble rise velocities.
At low pressures, a wide variation in bubble size was observed. Large stable bubbles tend to affect fluidization smoothness significantly. At higher pressure, bubbles possessed a more uniform size and were in general smaller. Consequently fluidization behavior was observed to be smoother at higher pressures.

INTRODUCTION
Industrial fluidized beds for the production of polymers are operated at pressures about 20 bars. Research on fluidized beds however is in generally performed at atmospheric conditions. Research at elevated pressure is difficult since steel vessels make (visual) access to the flow cumbersome.
Although most fluidization research is performed at atmospheric conditions the effects of pressure were investigated by several groups. Most groups use pressure fluctuation measurements to determine regime changes, such as Cai et al. (1). Canada and McLaughlin (2) made a regime map for varying pressure and velocities using pressure fluctuations in a 20 cm fluidized bed placed inside a pressure vessel. Minimum fluidization velocity and minimum bubble velocity at elevated pressures are investigated for example by Hoffmann and Yates (3), Chitester et al. (4), Sobreiro and Monteiro (5) up to pressures of 81, 65 and 35 bar, respectively. Besides regime changes Olowson and Almstedt (6-8) intensively researched bubble behavior at elevated pressure. Using pressure probes inside the fluidized bed Chan et al. (9) tried to obtain individual bubble properties. All these researchers used pressure fluctuations as their main information source, since visual access is difficult. For an overview of research on the effect of operating pressure on fluidization behavior we refer to the review papers by Sidorenko and Rhodes (10) and Yates (11).
Details about bubble emulsion structures cannot be found using pressure fluctuations. Therefore CFD models were used by Li and Kuipers (12) and Godlieb et al (13). From their CFD simulations it became clear that the bubble emulsion structure becomes less distinct and small chaotic moving bubbles emerge at elevated operating pressures. More recently, tomography techniques were used on pressurized fluidized beds to measure these effects. One of the most useful

measurement techniques in this respect is electrical capacitance tomography (ECT), which enables the measurement of the porosity distribution in fluidized beds. It is based on the differences in permittivity of the fluidizing gas and the solids material. ECT is a very powerful technique, since it non-invasive, fast and relatively cheap. Porosity tomograms can be measured at a frequency of 100 Hz. A drawback of ECT is the low spatial resolution of about one tenth of the bed diameter. A 30 cm diameter bed was chosen to reduce wall effect on the fluidization behavior. ECT is able to detect bubbles from 3 cm diameter. To our knowledge, only two groups performed ECT measurements on a fluidized bed under pressure. Sidorenko and Rhodes (14) were the first and they succeeded to perform measurements in a 15 cm bed. Cao et al. (15) performed ECT in a 20cm diameter bed up to 11 bar.
It is difficult to define experimental conditions that enable a fair comparison of results at different operating pressures. Three approaches were proposed in literature. A constant velocity is not advisable, since the minimum fluidization velocity (u_{mf}) decreases with increasing operating pressure. A constant excess velocity is used more frequently and adds a constant value to the minimum fluidization velocity. The third approach is to keep the ratio of the superficial velocity and the minimum fluidization velocity constant. For example Wiman and Almstedt (16) use a constant excess velocity, assuming that the total bubble volume remains constant. In this work we compare two measurement series: i) with a constant excess velocity equal to the minimum fluidization velocity at 1 bar and ii) with a superficial velocity equal to three times the minimum fluidization velocity.
Although in industry chemical reactions occur in the reactor, this work focuses on the fluidization behavior without chemical reactions. In all experiments nitrogen is used as a fluidization agent at room temperature. Nitrogen mimics the behavior of ethylene which is used in industry, since viscosity and density are similar. Nitrogen is used instead of air to avoid dust explosions, which can occur in polymeric dust.

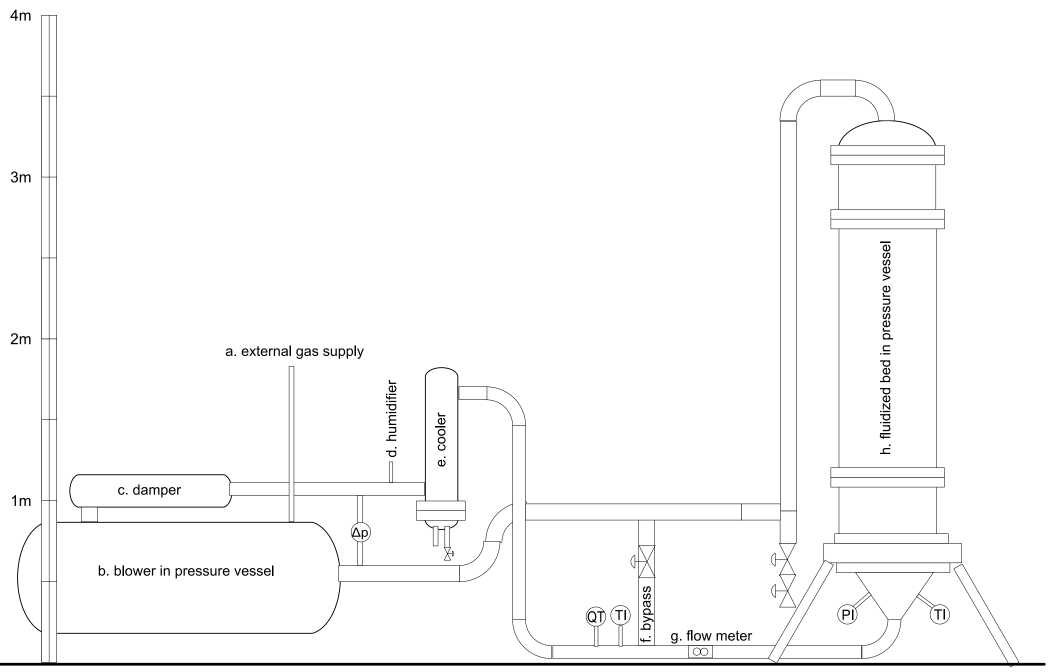

Figure 1: Schematic representation of the experimental set-up.

EXPERIMENTAL METHOD

Electrical capacitance tomography measurements were performed in a 30 cm diameter fluidized bed filled with 1.1 mm diameter polyethylene particles (density 925 kg/m^3) that was fluidized with nitrogen at 20 bars. To provide the required gas flow, the fluidized bed was placed in a closed, pressurized loop, containing a small roots blower, in which the gas was circulated. The loop is pressurized by an external compressor. A bypass was included in the loop (figure 1f), to have full flexibility in choosing the gas flow rate at different pressures. The blower produces a fluctuating gas flow. To stabilize the flow a damper is added (figure 1c). Because of friction between particles, particles get electrically charged, which may cause undesired effects such as particles clustering and the formation of sparks. To reduce the effect of electric charging we humidified the gas by spraying water into the loop, just after the blower (figure 1d). The water spray vaporizes and humidifies the gas stream. To remove the heat produced by the blower, a water cooler is placed just after the blower and humidifier (figure 1e). The fluidized bed comprises a 30 cm ID PVC tube situated inside the pressure vessel of 60 cm ID (figure 1h). The bed is filled with particles up to a static height of 60 cm, yielding a bed aspect ratio of two. The ECT measurement technique requires that the setup is made of materials with low conductivity. To this end, the bottom plate is made out of porous PE. A filter is placed on top of the fluidized bed to prevent particles and dust to exit the bed. The set-up is placed in a high-pressure bunker and is fully automatically controlled from outside the bunker.
The ECT sensor consists of twelve electrodes that are placed around the PVC tube. The capacitance measurements are normalized and reconstructed to a 32×32 pixel porosity plot, using a Landweber reconstruction algorithm with a relaxation parameter of 10^{-4} and 50 iterations and an inverted Maxwell concentration model. Porosity distributions can be measured for two horizontal planes simultaneously, which are selected from six available planes at different heights. The height of each of the electrodes is 5 cm and the bottom plate is placed directly under the first electrode. Guard planes are placed below and above the measurement planes, each having a height of 17 cm. A schematic representation of the electrodes is shown in figure 2.

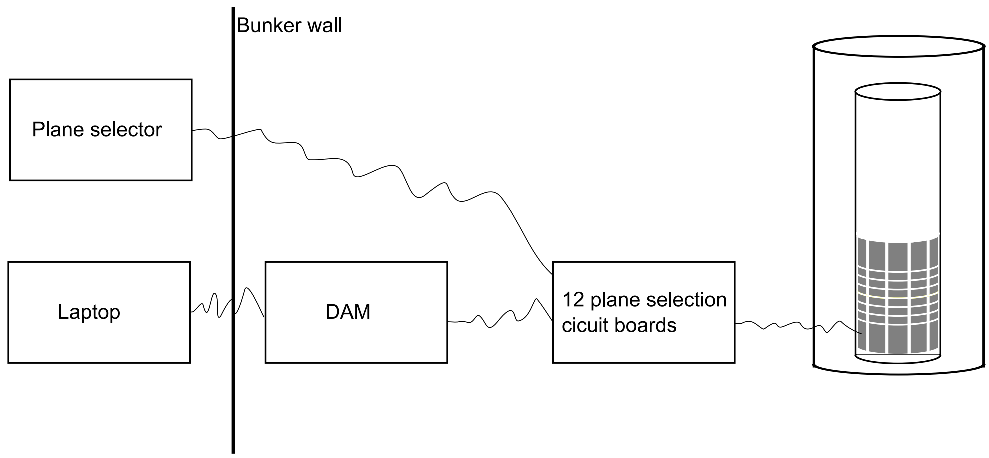

Figure 2: Schematic representation of all ECT units. The plane selection unit and the laptop are situated outside the bunker. The plane selection circuit boards are placed around the pressure vessel and are connected to the ECT electrodes.

Table 1: Gas velocity for a constant excess velocity and three times u_{mf} for 1.1 mm diameter polyethylene particles.

P [bar]	u_{mf}	u_{mf} + u_{mf} @1bar	$3u_{mf}$
1	0.30	0.59	0.89
2	0.25	0.54	0.74
4	0.20	0.49	0.59
8	0.15	0.45	0.45
16	0.11	0.41	0.34
20	0.10	0.40	0.30

RESULTS

In this work we present the results of two measurement series. First we will show results for a fluidized bed operated at a constant excess velocity. Subsequently these results are compared to a measurement series for a fluidized bed operated at three times the minimum fluidization velocity. We selected an excess velocity equal to the u_{mf} at 1 bar (0.3 m/s). The applied gas velocities are listed in table 1.

Porosity distribution

A probability density function (PDF) of the porosity is a useful representation of the porosity distribution. It clearly shows the bubble and emulsion fraction and porosity. The first step in making a porosity PDF is converting the measured normalized permittivity maps into porosity values, for which a 0.6 packing fraction for a randomly filled packed bed is assumed. The final step is making a histogram of all pixels over all time steps using a porosity bin size of 0.01. For each measurement about 10 million pixels are used.

The probability density function (PDF) of the porosity is shown in figure 3. It is clearly seen that with increasing pressure the peak around a porosity of 0.42 moves to higher porosities, in other words the emulsion become less dense with increasing pressure. Although a peak near a porosity of 1.0 is expected representing the presence of bubbles, this is not observed in the results. This is probably due to the low resolution of ECT and smoothing effects of the reconstruction techniques. Especially at high pressures it can be seen that the PDF is not zero at the right side of the plot. In fact about 8% of the PDF is higher than a porosity of 1.0. This unphysical measurement reading has the same origin as the lack of a bubble peak. The intermediate zone occurrence is increasing with increasing pressure.

In figure 4 a PDF of the porosity is shown at different heights. It is observed that in the bottom of the bed the intermediate zone occurs more often. The ECT resolution is too low to capture small separate bubbles. With increasing bed height the emulsion phase becomes denser and the bubble sizes increase, because of bubble coalescence. At 20 bar similar trends are observed but curves are shifted to higher porosities. At the lowest plane, just above the bottom plate, at 20 bar the porosity distribution is broad with a maximum at a porosity of 0.68, implying that neither a emulsion phase, nor a bubble phase is clearly observed.

From the averaged porosity data, radial profiles were constructed, by dividing the bed into 14 concentric rings, each with the same area containing 58 pixels.

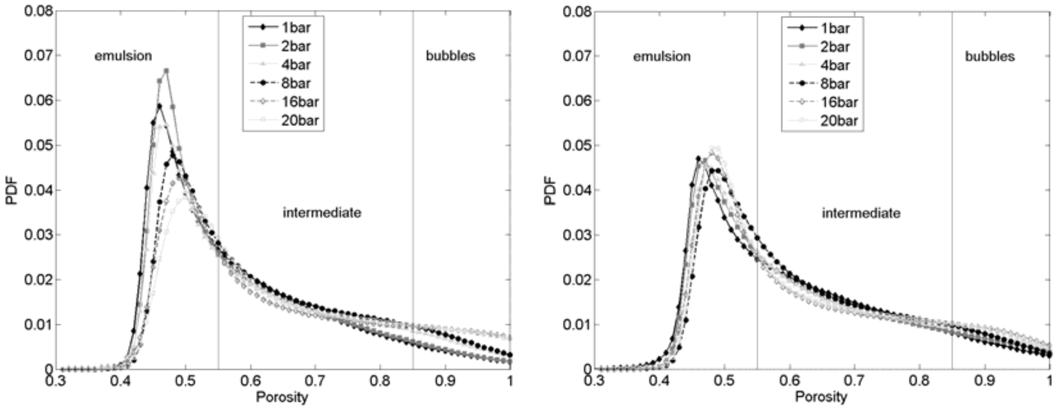

Figure 3: Probability density function (PDF) of the porosity at 10 cm to 15 cm above the distributor. A constant excess velocity of 0.30 m/s above u_{mf} (left) is compared to a measurement series using three times the minimum fluidization velocity (right).

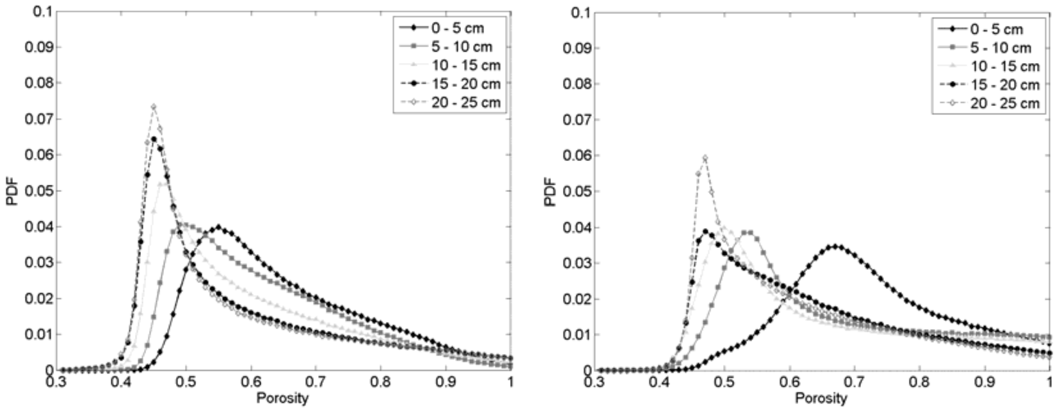

Figure 4: Porosity PDF at varying heights. A constant excess velocity of 0.30 m/s above u_{mf} is used. Left: 1 bar, right: 20 bar.

The resulting radial porosity distributions are shown in figure 5. A smooth fit is drawn through the measured data points to guide the eye. In the middle of the bed the porosity of the bed is increased with increasing pressure. So the bed expansion takes place in the centre of the bed. At the walls the porosity is slightly decreased.

Porosity fluctuations

Porosity fluctuations are a measure for the bubble size and vigorousness of fluidization. The porosity fluctuation is obtained by taking the standard deviation of the average porosity of a plane. Large bubbles containing no particles cause large fluctuations, while smaller bubbles containing particles cause minor fluctuations. The standard deviations of the porosity at four planes are shown in figure 5. Two trends are observed: i) with increasing height the fluctuations increase, due to bubble coalesce and the presence of large bubbles, and ii) with increasing pressure the fluctuations decrease. The latter is caused by the decrease of bubbles size and the less distinct difference between bubbles and emulsion as can be seen in figure 3.

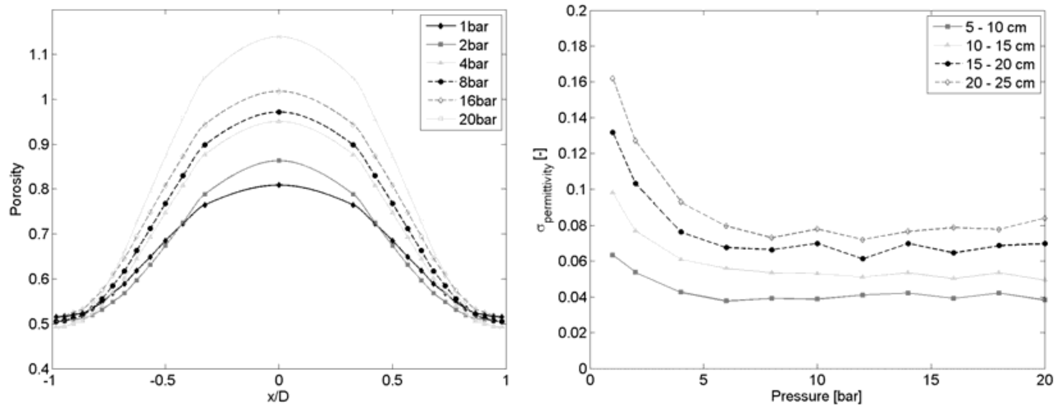

Figure 5: Radial porosity distribution at 10 cm above the distributor (left) and standard deviation of the normalized permittivity at different heights and pressures (right) at constant excess velocity.

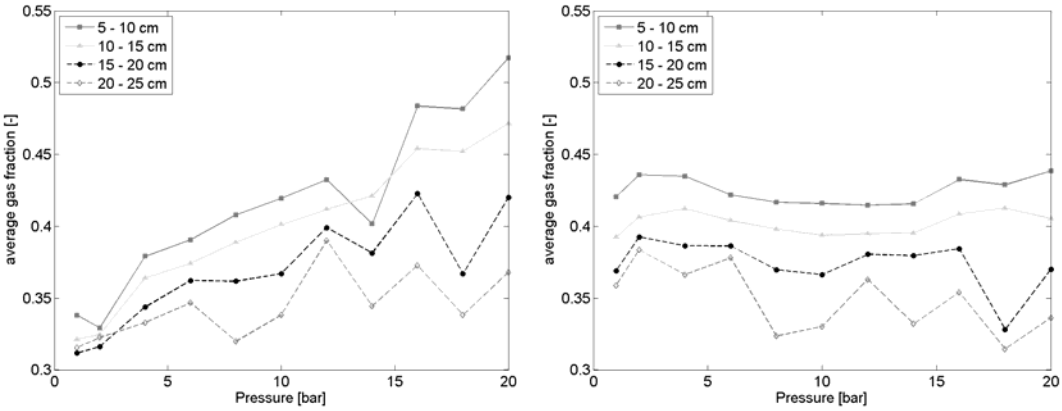

Figure 6: Average gas fraction at different heights for constant excess velocity (left) and $3u_{mf}$ (right).

Comparison of measurement series

In this section the flow behavior for two different superficial velocities are compared: a constant excess velocity of 0.30 m/s on top of the minimum fluidization velocity, and three times the minimum fluidization velocity. The former is based on the assumption that the excess velocity is responsible for the formation of bubbles. It assumes a constant total bubble volume. When a superficial velocity of three times the minimum fluidization velocity is used, it is assumed that this gives rise to similar fluidization behavior.

In figure 3 it was observed that the $3u_{mf}$ series show a constant PDF of the porosity, whereas the constant excess velocity series shows an increase of the emulsion porosity with increasing operating pressure. This result is confirmed by figure 6, where the average gas fraction (i.e. spatial and temporal average over the entire bed) is more or less constant for the $3u_{mf}$ series, whereas the average gas fraction increases with increasing operating pressure for the constant excess velocity series. For both series it is found that the average gas fraction increases with increasing bed heights, due to bubble coalescence.

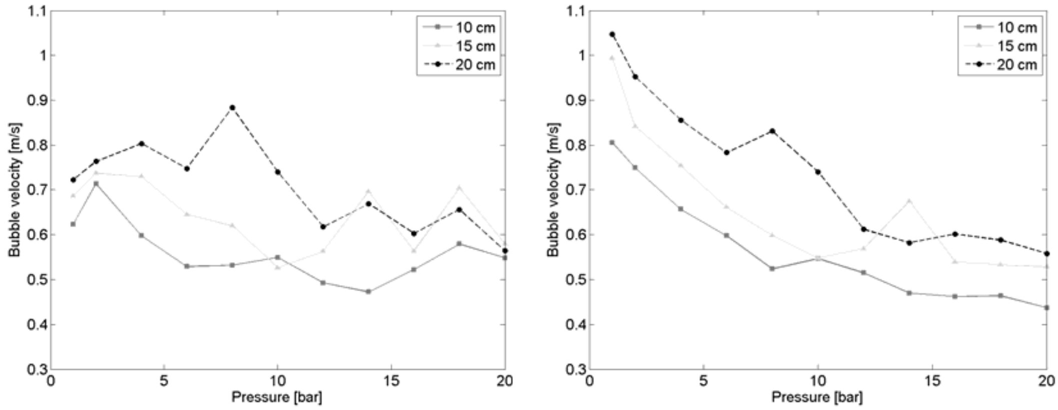

Figure 7: Bubble velocity at different heights obtained using an overall cross correlation for constant excess velocity (left) and $3u_{mf}$ (right).

By applying a cross correlation between the data from two subsequent planes, one can obtain a measure for the average bubble velocities in the bed. Surprisingly, the bubble velocity results show rather different trends compared to the average gas fraction results. In figure 7 it can be seen that the average bubble velocity is almost constant for the constant excess velocity series, while it is gradually decreasing for the $3u_{mf}$ series.
It can be concluded that it is not possible to keep the average gas fraction and the bubble velocity the same when the operating pressure is changed. While $3u_{mf}$ shows a constant porosity distribution and average gas fraction, bubble velocities decrease with increasing operating pressure and the constant excess velocity has a changing porosity distribution and rather constant bubble velocities.

CONCLUSIONS

In this work ECT was successfully used to investigate the flow behavior in a pressurized fluidized bed. For experiments with a constant excess velocity it is found that the emulsion phase becomes less dense and more bubbles and intermediate phase appear. Radial porosity distributions show that with increasing pressure the bed expansion occurs in the centre of the bed. The regions near the walls become slightly denser. Fluctuations in the porosity decrease with increasing pressure, which means that the bubbles become smaller or contain more particles. Finally, it is concluded that using the superficial gas velocity to scale the flow behavior with operating pressure gives ambivalent results. That is to say that experiments with constant excess velocity show constant bubble velocity and changing gas volume fraction, while experiments at three times the minimum fluidization velocity show constant porosity distributions and changing bubble velocities.

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