Borescopy in pressurized gas-solid fluidized beds

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A borescopic technique was used for finding the effect of pressure on the hydrodynamics of gas-solid fluidized beds. The results showed that solids radial distribution may become more or less uniform with increasing pressure depending on the superficial gas velocity. Moreover, it is found that the solids volume fraction of the emulsion phase may decrease at relatively high pressures, only in the central region of the bed. Additionally, it is observed that with increasing pressure the bubble size generally decreased in the central regions and increased near the wall regions. This trend was more complicated at low excess gas velocities. The number of bubbles increased for the central regions and near the walls for all the performed experiments. However, this parameter showed a different trend at other radial positions. © 2018 The Authors AIChE Journal published by Wiley Periodicals, Inc. on behalf of American Institute of Chemical Engineers

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Introduction

Gas-solid fluidized beds have various industrial applications like food processing, polymerization, combustion, gasification, catalytic cracking, and drying. Some of these operations like polymerization or combustion are performed at elevated pressures.\(^1\)\(^,\)\(^2\) Even though these types of contactors have been used in different industrial applications but many aspects of their behavior like the effect of pressure on their behavior is not completely understood. For this reason, several studies for finding the effect of pressure in fluidization of different types of particles have been conducted during the last couple of decades. Not all of these studies are in agreement with each other which clearly show the necessity of further investigation on this important topic.

In 1973, Geldart\(^3\) reported that increasing the operating pressure for some Geldart B particles may make the fluidization look like a fluidization for Geldart A particles. In 1980, King and Harrison\(^4\) claimed that the pressure does not have a significant effect on the bubble size and their stability for large particles if the excess gas velocity is kept constant. Conversely, the bubbles become smaller with pressure for fine powders typically smaller than 100 \(\mu\)m diameter. Sobreiro and Monteiro\(^5\) also investigated the effect of pressure and they observed that the minimum fluidization does not change with pressure for small or light particles and it decreases with pressure for large or dense particles. Furthermore, they did not find any relationship between the gas volume fraction at minimum fluidization condition with pressure. Two years later, Rowe\(^6\) found similar results for various particle sizes. A few years
later, Hoffmann and Yates$^7$ performed x-ray experiments for particles with the size of 184 and 450 $\mu$m diameter and for pressures up to 81 bar. In contrary to the King and Harrison’s findings,$^8$ they claimed that the bubbles become smaller over most of the pressure range for 450-$\mu$m particles. They also found that the bubbles have a higher tendency to distribute nonuniformly in the radial direction at elevated pressures.

Olowson and Almstedt$^9$ used capacitance and pitot-static pressure probes for Geldart B particles. They found that the average bubble rise velocity and average bubble fraction increase with pressurizing the bed. They also found that the bubbles tend to redistribute themselves toward the center of the bed with increasing the operating pressure. Moreover, they found that the minimum fluidization velocity decreases with pressure according to the Ergun equation$^{10}$ for Geldart B or D particles. Finally, they found that the bubble size increases and then decreases with increasing the operating pressure. In 2004, Sidorenko and Rhodes$^{11}$ used electrical capacitance tomography (ECT) to measure the bed voidage, average cycle frequency, and average absolute deviation of bed voidage. They found that the pressure has no influence on these two latter parameters.

In 2012, Godlieb et al.$^{12}$ published their ECT experimental findings for 0.5 mm glass and 1.0 mm linear low-density polyethylene (LLDPE) particles at 1–20 bars. They showed that the emulsion phase shrinks with increasing pressure at constant excess gas velocities. This effect was less significant for glass particles compared to the results of LLDPE particles. Moreover, they showed that the gas volume fraction increases in the central region of the bed with increasing pressure for LLDPE particles. Conversely, this effect was not monotonic for glass particles. Additionally, they found that the bubble velocity decreases and average gas volume fraction increases with pressure. In general, their experimental findings showed a smoother fluidization at higher pressures. These are only some of the available experimental studies which are sometimes conflicting.

Besides the experimental works, several numerical studies on the fluidization at elevated pressures have been conducted as well. For instance, Li and Kuipers$^{13}$ used combined computational fluid dynamics with discrete element model (CFD-DEM) for two-dimensional (2-D) beds and for particles with the size of 0.949 mm and a density of 1170 kg/m$^3$. They found that the particle collision frequency decreases with pressure and the gas-solid interaction gets enhanced which lead to the suppression of large bubbles formation. Godlieb et al.$^{14}$ also studied this topic with using the CFD-DEM for 0.5 mm particles with the density of 925 kg/m$^3$ and at 1–64 bars for a three-dimensional (3-D) bed. They found that the emulsion phase becomes less distinct, while the bubble phase gets expanded. They also found that the particles have larger distances toward each other at elevated pressures. There are several more simulation studies on this topic in the open literature which we refer the interested readers to Refs. 15–19.

Due to the importance of this topic from industrial and academic perspective, we initiated a research on fluidization at elevated pressure and some of our results are presented here. In this work, we used an imaging technique to investigate the effect of pressure on fluidization behavior. For imaging techniques, visual access is required, which is not straightforward for pressurized setups. Therefore, we designed a borescope and used borescopy to obtain images from the interior of the fluidized bed. Several other researchers also used borescopes in the fluidization field successfully.$^{20–22}$ In this way, we could obtain visual access inside of 3-D beds with nontransparent walls. Conversely, the presence of the borescope intrudes the system. After installing the borescope into a bed, we performed various experiments at different pressures and applied various image analysis techniques to find out some indications for bubble size and their pattern of movement. Furthermore, we also found some indications on the distribution of solids in the system at different operating pressures and superficial gas velocities. This information gives more insights on the behavior of bubbling fluidized beds at elevated pressures and it can also be used for qualitative and quantitative validation of simulation models. Using simulation data for further improvement of image analysis techniques can enhance our findings from borescopic images. This technique has a high spatial and temporal resolution that cannot be obtained by some other techniques like ECT. In addition, in contrary to point measurement techniques, it can give us information of a specific area at a time. For this reason, we can gather a lot of valuable data. Furthermore, the borescopic facility can be implemented to a pressurized setup with a reasonable price.

We used this technique for 0.5 mm diameter glass particles with a density of 2500 kg/m$^3$ at 1–16 bar and for two different excess gas velocities. In the next sections, we described the applied experimental setup and the borescopic facility. Then, we discussed the experimental conditions and the obtained results. We measured the average intensity profile at different radial positions, which provides inside in the preferential radial distribution of solid particles or bubbles as a function of operating pressure and superficial gas velocity. We also obtained the probability distribution function (PDF) of the image intensity to see how the bubble and emulsion phase may expand or shrink with pressure or velocity. Finally, we obtained the bubble size and number in all the images and discussed the effect of pressure and superficial gas velocity on these parameters as a function of the radial position.

**Experimental Methodology**

**Fluidized bed setup**

The fluidized bed setup used in the work is the same setup as used by Godlieb et al.$^{12}$ This bed is cylindrical and has the inner diameter of 0.3 m and it can safely be operated up to 16 bar. The setup can be filled with pressurized nitrogen and this pressurized nitrogen can be recirculated in the system as a fluidization agent. A simplified schematic representation of this setup is presented in Figure 1.

**Borescopic system**

The applied borescopic system consists of two long concentric borescopes: the inner one is equipped with lenses and is designed for transferring images to the camera and the outer one conducts light for illuminating the field of view. We will refer to the inner and the outer borescopes as observation and illumination borescopes, respectively. The dimension of the borescopes and their elements are presented in Figure 2. The facilities also includes two ITOS phaser 3000 OSRAM light sources$^{23}$ that can be used for technical or medical endoscopy and a high-speed OPTRONIS CP80–4–M–500 camera.$^{25}$ The camera and the two light sources are connected to the observation and the light borescopes, respectively. The borescope has been inserted into the fluidized bed from the top. Figure 2 shows that there is an ocular at the tip of the borescope. This
pressure according to the Ergun equation for Geldart B or D increase with pressurizing the bed. They also found that the pressure probes for Geldart B particles. They found that the particles have larger dissections.

In this work, we used an imaging technique to investigate the fluid dynamics of Geldart D emulsion in a fluidized bed. We initiated a research on fluidization at higher pressures, for which we refer the interested readers to Refs. 15–19. Later, Hoffmann and Yates performed x-ray experiments for 0.5 mm particles with the size of 184 and 450 mm diameter and for particles with the size of 184 and 450 mm diameter. They also found that the bubble size increases and the gas-solid interaction gets enhanced which lead to the suppression of large bubbles formation. Godlieb et al. also found some indications on the distribution of solids in the central region of the bed with increasing pressure for various image analysis techniques to find out some indications.

Results and Discussion

Radial profile of image intensity

As explained earlier, a relatively high time-averaged image intensity in one position or condition corresponds to a large time-averaged solid volume fraction at that position or condition. Figure 3a shows this parameter over time for Case A1 at r/R = 0.807 before, during, and after passing of a bubble in our field of view, whereas Figure 3b shows this parameter for Case A1 at two different radial positions; r/R = 0.113 (close to the bed center) and r/R = 0.807 (close to the bed walls). This figure clearly shows that for this condition, bubbles have a higher tendency to pass through the central region of the bed rather than through the annular region near the wall. Moreover, we can also see that the image intensity fluctuations have higher amplitudes in the central region than near the wall which indicates either, a higher bubble volume fraction, larger bubble frequency, or a sign of larger bubbles passing in the central region.

We also calculated radial profiles of image intensity, which shows how the solids tend to be distributed radially in a qualitative manner. We need to keep in mind that the average image intensity and average volume fraction are not linearly correlated to each other. The image intensity not only changes with the number of particles, but it also changes with the distance of the particle to the tip of the borescope. If a particle is further away from the borescope, it will appear darker. Besides that, particles can make a shadow over each other, which will change the correlation between the intensity and the solids volume fraction. Moreover, when we capture a particle in an image, we have no information if there are more particles behind the captured particle. The radial profile of the image intensity only shows us the preferential distribution of the solid phase, but it does not give any quantitative information about the radial solids volume fraction distribution. Nonetheless, it can be used to give qualitative insight on how the solids preferential distribution may change radially depending on superficial gas velocity and operating pressure. Figures 4 and 5 show our findings on the radial profile of average image intensity at various operating pressures and superficial gas velocities. The solid and dashed lines in these two figures represent the polynomial fits to the experimental data.

Figure 4a shows that with increasing the pressure, at \( u_{ex} = 0.08 \) m/s, the image intensity near the center of the bed decreases. We also observed a more nonuniform radial gas/solid distribution at higher pressures for this excess gas velocity. We observed a similar trend at \( u_{ex} = 0.27 \) m/s until 4 bar. From 4 to 16 bar, we observed that the image intensity near...
the central regions does not increase significantly but the image intensity from \( r/R \approx 0.5 \) till \( r/R \approx 0.9 \) increases. It seems that depending on the excess gas velocity, increasing the operating pressure can cause a more uniform or more non-uniform radial distribution of solid particles.

We also observed that for Case A1, the minimum average image intensity occurs at \( r/R \approx 0.5 \) and the maximum image intensity occurs near the wall boundaries. So, we expect that the highest bubble fraction occurs at \( r/R \approx 0.5 \) at least at the investigated height in the bed. Even though the difference in average image intensity at \( r/R \approx 0.5 \) and near the walls is not very significant for this case, we note that the variation of image intensity is small for all test cases. There is still a large difference in the bubble formation rate for Case A1 near the center of the bed and for the same case near the walls. Figure 3b shows this difference very well. With increasing the gas velocity, we observed that the minimum image intensity occurs at \( r/R \) very close to the bed center \( (r/R \approx 0.11) \). So, increasing the gas velocity caused a more nonuniform bubble distribution in the radial direction. There can be various reasons for this observation. For example, it can be due to increased bubble coalescence with increasing the superficial gas velocity. Conversely, we observed a different behavior from 8 bar till 16 bar. At these operating pressures, the average image intensity in the middle of the

### Table 1. Experimental Conditions

| Case | \( P \) (10^5 Pa) | \( u_{mf} \) (m/s)^2 | \( u_{ex} \) (m/s) |
|------|-----------------|---------------------|-----------------|
| A1   | 1.0             | 0.21                | 0.08            |
| A2   | 1.0             | 0.21                | 0.27            |
| B1   | 2.0             | 0.19                | 0.08            |
| B2   | 2.0             | 0.19                | 0.27            |
| C1   | 4.0             | 0.17                | 0.08            |
| C2   | 4.0             | 0.17                | 0.27            |
| D1   | 8.0             | 0.14                | 0.08            |
| D2   | 8.0             | 0.14                | 0.27            |
| E1   | 16.0            | 0.11                | 0.08            |
| E2   | 16.0            | 0.11                | 0.27            |

\( d_p = 0.5 \) mm, \( \rho_p = 2500 \) kg/m\(^3\); 45015-427-W1 by Sigmund Lindner.\(^{26} \) Measurement height: 0.19–0.23 m above the gas distributor. Bed aspect ratio: 1.0. Light sources: two ITOS phaser 3000 OSRAM.\(^{25} \) Camera: OPTRONIS CP80-4-M-50025; Imaging frequency: 1000 fps.

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\[\text{Figure 2. Dimensions of borescopic facility and its elements.}\]
The gas phase tends to move from the areas with lower resistance. As there is a higher friction near the walls and particles tend to fall near the bed walls, the gas mostly passes through the central regions. With increasing the gas velocity, there will be an increased bubble formation and subsequently more bubble coalescence in the system which leads to a higher gas volume fraction in the central regions. That is why the average image intensity for Case A2 is more nonuniform than the one for Case A1. At the same time, with increasing the gas velocity or the operating pressure, the gas phase will have more momentum. Therefore, it will be easier for the gas phase to overcome the friction and the resistance near the walls. So, if the gas velocity or operating pressure are sufficiently large, the gas phase will have such a large momentum that it does not have such a strong preference to go through the central regions compared to the regions close to the walls. That is why we have observed a more uniform trend of radial average image intensity for relatively large velocities and pressures, like for Case E2.

As mentioned earlier, some researchers\textsuperscript{7,8} claimed that the solids or bubble radial distribution becomes less uniform and some\textsuperscript{12} did not find such a clear trend for some of their experiments. Our results show that the solids or bubbles radial distribution can become more uniform or less uniform.
depending on the other experimental conditions. For instance, we observed less uniform radial solids and radial bubble distribution with increasing the operating pressure when the excess gas velocity is relatively low. Conversely, we found an opposite trend at relatively large excess gas velocities. In other words, the effect of pressure might change at different superficial gas velocities, particle-wall frictions and particle types because the radial distribution of solids or bubbles is mainly dependent on the bubbles’ interactions, gas and bubbles momentum, and resistance near the walls. Thus, the trend of results might be different at different operating conditions.

Moreover, we found that at 16 bar and only at \( r/R = 0.113 \) the average intensity of emulsion phase is smaller than its corresponding value for the rest of the cases. We found that the average image intensity is around 230 and it drops when a bubble or a few bubbles are passing the field of view. In other words, the average image intensity when no bubble is passing by is around 230 and therefore, we can attribute this value to the emulsion phase. This value is almost the same for all cases regardless of the gas velocity, radial position, or operating pressure, except at 16 bar and \( r/R = 0.113 \), where it drops to \( \sim 220 \). Godlieb et al.\(^{29}\) also reported that emulsion phase becomes less dense with increasing the operating pressure in the CFD-DEM simulations which is in agreement with our findings. Figure 6 shows the average image intensity for Case E1 at \( r/R = 0.113 \) and \( r/R = 0.893 \). This figure also shows two sample images of emulsion phase for these two measurement points. We can clearly see that the solids volume fraction in the emulsion phase is different for these two images.

**Probability distribution of image intensity**

In addition to the time-average of the image intensity, we also calculated its probability distribution or PDF. The PDF of the image intensity shows how the amount of bubble phase and emulsion phase changes with operating condition and radial position. For this purpose, we used 50 bin intervals for the intensities between 0 and 255, and we used Eq. 2 to calculate the image intensity PDF:

\[
\text{PDF}_I(\text{bin id}) = \frac{1}{N_{px}} \sum_{i=1}^{N_{px}} I_b
\]

\[
I_b = \begin{cases} 
1 & \text{if } I_{bin} - \Delta/2 < I < I_{bin} + \Delta/2 \\
0 & \text{else}
\end{cases}
\]

Where \( \Delta \) is the bin size for calculation of PDF and in this work it is equal to 255/50 = 5.1. Figure 7 shows the PDF of image intensity at three different radial positions for Case A1. The results showed that for Case A1, the bubble volume fraction increases from \( r/R = 0.113 \) to \( r/R = 0.46 \) and then decreases from \( r/R = 0.46 \) to \( r/R = 0.893 \). At the same time, the emulsion phase shrinks from \( r/R = 0.113 \) to \( r/R = 0.46 \) and then gets expanded.

We also calculated the PDF of image intensity for other experimental cases. Figure 8 shows the effect of pressure and superficial gas velocity on this parameter at \( r/R = 0.113 \).

Figure 8 shows that the emulsion phase shrinks with increasing pressure. At \( u_{ex.} = 0.08 \text{ m/s} \), the bubble phase grows with increasing pressure until 8 bar. When the pressure further increases to 16 bar, the distinction between the bubble phase and the emulsion phase becomes less pronounced. At \( u_{ex.} = 0.27 \text{ m/s} \), we observed shrinkage of the bubble and emulsion phases simultaneously, while the intermediate phase gets expanded. In other words, the distinction between the bubble and emulsion phases becomes less noticeable which has also been observed by some other researchers.\(^{29}\) Figures 8c, d show the effect of superficial gas velocity on the PDF of the image intensity. Figure 8c shows that at 1 bar, the bubble phase gets a higher fraction from the total images with increasing gas velocity. Figure 8d shows that this effect is less noticeable at 16 bar. We should keep in mind that the presented PDF is only obtained for one radial position.

![Figure 6. Average image intensity for Case E1.](image)

![Figure 7. PDF of image intensity at different radial positions for Case A1.](image)
Effect of pressure and gas velocity on the bubble size

The parameters like the image intensity average and PDF do not show all the details. For example, if we have two small bubbles in an image, we will only see a very low image intensity but we do not know if there is one large bubble in the field of view or a few small ones. For this reason, we also calculated the bubble areas from the image intensity data. For this purpose, we applied a median filter with the size of 25 by 25 pixels on the images and then binarized them with the desired threshold. It should be added that our field of view was 301 × 1201 pixels (corresponding to 1 × 4 cm²) and we used the threshold of 0.8 × 255 to binarize the images. Then, we could detect the black regions which indicate the bubbles. We also calculated the size of these black areas. This information does not show the exact bubble size as the field of view is quite limited and the images do not show the complete picture of most of the bubbles, especially the large ones. On the other hand, similar information can be extracted from the simulation results as well. So, such experimental data can be very useful for validation of simulation models especially at elevated pressures for which there is hardly any alternative data available in the open literature. For the sake of argument, we will from here onward refer to the dark regions in the images as bubbles and determine their diameter from the images.

Figure 9 shows radial profiles of the arithmetic average bubble size for all the experimental cases. Images were recorded for a duration of 7.5 s at a frequency of 1000 Hz for every measurement. So, if a bubble was very small and slow, it was captured more often than large and fast-moving bubbles. This leads to a bias, similar to cases where a bubble does not move vertically. Therefore, one should take care in the interpretation of the results and comparing with simulation data. We also calculated the relative number of bubbles using Eq. 3 and the final results are presented in Figures 9b, d. In this equation, NB and NBA1 are the total number of captured bubbles for a desired case and for Case A1, respectively. Moreover, Nb is the number of observed bubbles in one taken image.

\[
\text{NB} = \sum \frac{N_b}{\text{All the 7500 images}} \quad \text{NB}_{A1} = \sum \frac{(N_b)_{A1}}{\text{All the 7500 images}}
\]

(3)

We found that in the bed center the bubble size mostly decreased with pressure, and increased near the walls at \( u_{ex} = 0.27 \text{ m/s} \). We also observed that the bubble size did not change significantly with the radial position for Cases E1, D2, and E2. Except at 2 bar, the number of observed bubbles increased with pressure in the bed center and near the wall. As stated earlier, King and Harrison\(^7\) claimed that the bubble size does not change with pressure for Geldart B particles while some other researchers\(^8,9\) found different results. Our results with the borescope are more in accordance with the latter. The borescopic results showed that the pressure changes the bubble size and this change is not monotonic and it varies depending on the other factors like superficial gas velocity or the radial position. For instance, we observed that the bubble size and the number of bubbles mostly increased with pressure near the wall boundaries. Further studies on the effect of pressure at different radial positions can be very helpful to understand the behavior of pressurized fluidized beds.
Limitations and Future of Borescopy

Every technique has some disadvantages and limitations and it is necessary to consider these limitations while analyzing their outcomes. This also helps us to find the ways to improve these techniques. Borescopy has its disadvantages and limitations and some of the most important ones are discussed in this section. First of all, we know that borescopy is intrusive. To minimize its influence, we should make the size of the borescope as small as possible. This conflicts with the desire to have a large field of view to get more information at a time. So, there is a compromise in this aspect and definitely more research can be done to find the optimum design. The second important factor in borescopy is lighting. Lighting is a very important factor in any imaging technique and this matter becomes more vital with increasing the number of lenses or the length of the borescope. For this reason, we used a very strong light source and opaque white particles to have the best possible contrast and brightness in our images. The other limitation of borescopy is difficulty in detecting particles that are out of focus. Sometimes, depending on the number of out of focus particles and their distance to the ocular, we may still see them in the images quite brightly. Then, the calculated size of the dark regions will be smaller than the bubble size even if we can capture the whole bubble in our field of view. The other limitation of borescopy is its need for visual access. If some particles are very close to the borescope, the light intensity will be very large and they may partly be blocking visual access to nearby particles. So, two images can have the same intensity but they can correspond to different solids volume fraction. On the other hand, when we average the results over time; we do expect that these errors cancel out to some extent. This limitation also exists for normal digital image analysis techniques used to study the flow in pseudo-2-D fluidized beds. There are some ways for correlating the solids volume fraction to the image intensity or for detecting the out of focus particles. Usually, however, these suffer from large uncertainties. Nonetheless, we do think that applying these techniques can be a first step in improving the analysis of borescopic images and it is recommended to extend the analysis for further research in this area.

Conclusions

We successfully applied a borescopic technique for capturing the behavior of pressurized gas-solid fluidized beds. This technique could give us very valuable information that can be used for validation of numerical simulations. We used this experimental technique at two different excess gas velocities and at five different operating pressures between 1 and 16 bar. After capturing the images with the borescopic system and by interpreting the image intensity data, we could find out the preferential radial solids distribution at different pressures and superficial gas velocities. In the performed experiments, the solids distribution became more nonuniform in the radial direction at low excess gas velocity and it became more uniform at relatively large excess gas velocity. So, it seems that depending on the excess gas velocity, increasing the operating pressure can cause either a more uniform or less uniform radial distribution of solid particles and bubbles. Besides that, we also obtained the approximate bubble size and our results showed that the bubble size decreased with pressure in the bed.
center, while it increased close to the wall. We also observed that the bubble size did not change significantly with the radial position for Cases E1, D2, and E2. We also found that, except at 2 bar, the number of observed bubbles in all the images increased with pressure in both the central and near-wall regions. Our results showed that the effect of pressure on the fluidization behavior is not monotonic and it is highly dependent to the superficial gas velocity or the radial position.

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Notation

- CFD = computational fluid dynamics
- DEM = discrete element model
- ECT = electrical capacitance tomography
- \( N_b \) = number of bubbles in one image
- \( N_{b,7500} \) = number of bubbles in all the 7500 images of one measurement
- \( N_{b,7500} \) = size of dark regions/bubble size, m
- THM = temporal histogram method
- \( u_{\text{mf}} \) = minimum fluidization velocity, m/s
- \( u_{\text{ex}} \) = excess gas velocity, m/s

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