Qualitative gas holdup measures

Quantitative gas holdup measures

Probe Effects on the Local Gas Holdup Conditions in a Fluidized Bed

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Abstract

Fluidized beds are found in the energy production industry, and knowing their hydrodynamic conditions, such as local gas holdup or volumetric gas fraction, is important for effective operation. Local measurement probes are commonly used to measure local gas holdup. Although the probes are typically as small as possible to mitigate their influence on the local conditions, the invasive nature of this measurement technique has the potential to alter the fluidized bed behavior. This study used a noninvasive measurement technique, X-ray computed tomography (CT) imaging, to determine the local time-average gas holdup everywhere within a 10.2 cm diameter fluidized bed filled with 500-600 μm glass beads in which simulated probes were inserted. Three different simulated probe tips (pointed, rounded, and flat) and two different orientations (horizontal and vertical) were investigated at four different bed heights and two different fluidization velocities. The results show increases in local time-average gas holdup when the probes were present, but the scale of the effects was dependent upon the height at which the probes were placed; the lower the probe within the fluidized bed, the larger the local effects. The shape of the probe tip did not show any differences in the local gas holdup. On the

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other hand, probe orientation was an important factor, with the horizontal orientation showing a sustained increase in gas holdup values farther from the probe. The two different flow rates used in this study ($1.5U_{mf}$ and $3U_{mf}$, where U_{mf} is the minimum fluidization velocity) also showed differences in the amount of variation in gas holdup, but the trends were inconsistent. Overall, the local hydrodynamic effects of the simulated invasive probes of this work were minimized when: (i) the probes were placed in the central part of the bed, outside the aeration region and top of the bed, (ii) the fluidized bed was operated at higher superficial gas velocities, and (iii) the probes were mounted in a vertical orientation.

Keywords:

Fluidized Bed
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1. Introduction

Fluidized bed reactors involve gas-solid systems that are often chaotic in nature, and thus, are difficult to characterize. Visualization of the reactor hydrodynamics beyond the wall region is generally not possible, even when allowing for optical access in the reactor walls. Since the interior characteristics of the bed play a vital role in the overall structure and effectiveness of the fluidized bed, it is necessary to measure the bed properties throughout the bed. Both invasive and noninvasive measurement techniques have been used in the past to quantify fluidized bed characteristics [1]. Invasive methods include different types of measurement probes to detect various interior properties. Although invasive probes are designed for minimal flow influences [2], anything inserted into the flow could potentially affect the flow conditions. The current study

uses the noninvasive measurement technique of X-ray computed tomography (CT) to quantify the effects of simulated invasive measurement probes on the local time-average gas holdup in a fluidized bed.

Noninvasive measurements are the preferred method for analyzing the internal characteristics of a fluidized bed because they ensure that the measurement itself has no effect on the resulting measured value. Noninvasive techniques range widely for fluidized beds and include simple optical analysis, X-rays, γ -rays, capacitance tomography, etc. [3]. Optical analysis is extremely limited owing to the fact that the fluidized solids tend to be opaque in nature and even clear substances become difficult to see once they are fluidized. In order to use optical techniques, two dimensional beds are often employed (see, for example, [4]), which raises concerns about whether or not two-dimensional beds are characteristic of three dimensional beds, or indeed, large scale beds [1].

X-rays have been used to study fluidized beds since the 1950s [3] and are an effective tool in characterizing opaque multiphase flows. X-rays offer lower risks from ionizing radiation when compared to γ -rays. Modern X-ray techniques offer excellent spatial resolution, although there is often a tradeoff in temporal resolution. This is especially true in the X-ray CT imaging that is employed by this study. Therefore, the data obtained from this method is necessarily averaged over time.

X-ray CT imaging has been employed successfully with fluidized beds in past studies. Franka and Heindel [5] used X-ray CT imaging to study a fluidized bed modified for side air injection. They were able to visualize and measure the plume from the side air injection using X-ray CT's, where the side air injection simulated the immediate volatilization of biomass being injected into a fluidized bed gasifier. Drake and Heindel [6] used the time-average gas holdup

calculated from X-ray CT imaging to show that fluidized beds were uniform away from the aeration region and that tests using the same conditions were repeatable over time. Drake and Heindel [7, 8] were also able to successfully employ X-ray CT imaging for use in comparing the flow structure of two different diameter beds modified for side-air injection. Escudero and Heindel [9] used X-ray CT imaging of a fluidized bed to show the effects of an acoustic field on the time-average gas holdup.

There has been an increase in the capabilities and effectiveness of various noninvasive techniques [3]; however, they may be prohibitively expensive or not even possible to use in certain systems. This is especially true in larger scale reactors or systems that involve pressurized and/or high temperature conditions that more closely model industrial conditions [10]. For systems incapable of being characterized through noninvasive means, measurement probes become a necessity.

Measurement probes used in fluidized bed studies tend to vary drastically in the type as well as the shape. In general, these probes measure characteristics in either the fluid phase or the solid phase [1]. The three most popular probe types are optical, capacitance, and pressure sensor probes. Most cases involve two or more probes in order to measure the local differences at various locations within the bed, whether it is at different axial positions along the reactor walls or at different radial positions within the bed. This means that any effects produced by the probe on the flow structure are compounded and could easily affect subsequent measurements.

Optical probes can measure either the solid or fluid phase of the multiphase systems. Optical probes pose a unique design challenge as they usually require that light be both transmitted and received. As such, optical probes seem to have the largest variations with probe geometries and size [11]. Past studies have used bundles of fiber optics arranged in more

conventional probe shapes [12-15], whereas other studies have designed new probe configurations like U-shaped probes [16, 17].

Capacitance probes measure the changing capacitance of the bed and are based on the principle that the solids concentration in a fluidized bed is related to the capacitance that is built up in the system [1]. Capacitance probes can either be shaped as wands, or as two parallel plates which can be quite small and fit within a probe [18] or quite large (e.g., 12×12 mm) [2].

Pressure sensors are perhaps the most common measurement and have been a part of fluidized bed study since its inception [1]. They commonly involve pressure transducers lined up flush against the interior wall of the bed. Although these types of sensors are assumed to have little to no effect on the flow, especially when compared to more invasive probes, they still could have an effect on the local flow conditions [6].

Regarding inserts on fluidized bed hydrodynamics, Kaza [19] defined the blockage ratio as the ratio of the cross sectional area that is blocked by the insert to the cross sectional area of the bed without an insert. The larger the blockage ratio, the greater the effect a vertically oriented insert will have on the hydrodynamic structure of a fluidized bed. Kaza determined the blockage ratio was independent of the shape of the insert.

Rowe and Everett [20] completed preliminary X-ray radiography studies of the effect of vertical and horizontal rod inserts on fluidized bed hydrodynamics. It was found that the vertical rods had no effect on the overall bubble behavior in the bed unless the rod was placed so that the generated bubbles had the opportunity to symmetrically surround the rod. In this case, the bubbles tended to follow the path of the rod upwards. Vibrating the vertical rod also caused the bubbles to stabilize along the rod, forming a bubble chain and affecting the bubble pattern throughout the bed. When the rods were horizontal, they were permanently enveloped by air

pockets or bubbles, particularly at higher flow rates, and bubbles tended to rise regularly from the horizontal rod.

A more recent study of the effect of probe size was completed by Ellis et al. [11]. They used three different sizes of optical probes and determined that the probe size affected the scale of the recorded gas holdup fluctuations.

Rowe and Masson [10, 21] also looked specifically at the effects of measurement probes on fluidized bed hydrodynamics. They used X-ray radiography and optical probes concurrently in order to assess the differences between measured bubble diameters and bubble rise velocities. They completed two studies; one that found no correlation in measured values at all between the probe and radiographs, and the second exhibited a weak correlation between the two techniques. They concluded that probes used as measurement tools in fluidized beds should be used with caution, and if possible, be calibrated using noninvasive methods as a reference; this was also concluded by Geldart and Kelsey [18]. Note that the X-rays used by Rowe and Masson [10, 21] were single projection radiographs and lacked the ability to accurately describe the bubbles in three dimensions.

Maurer et al. [22] used a fast X-ray system to noninvasively image bubble dynamics below and above horizontally oriented optical probes. The bed was operated at the minimum fluidization velocity while single bubbles were centrally injected into the bed. They determined that the bubble size and shape, as well as the rise velocity of a single bubble, were not significantly influenced by the inserted probes.

Rowe et al. [10, 20, 21] clearly showed that probes have an effect on bed hydrodynamics, while Maurer et al. [22] indicated there is no effect. In these studies, however, they only focused on individual bubbles. The bubble characteristics are an important variable used to describe

fluidized bed behavior, but measurements of specific bubbles tends to lack enough information to characterize the full scale that probe effects may have on fluidized bed hydrodynamics. The scope of the viewing axis was also limited and was incapable of viewing the fluidized bed in its entirety, so the measurements were limited.

Dubrawski et al. [23] compared various invasive and noninvasive measurement techniques using the same (or nearly the same) fluidized bed in each test. They transported the fluidized bed and materials to various laboratories with different measurement capabilities to compare measurement methods. Overall, they concluded that the invasive measurement techniques resulted in slightly higher gas holdup measures and slightly higher deviations from the overall mean values when compared to the noninvasive measurement techniques.

While previous studies in the literature have tried to quantify the effects that measurement probes have on fluidized bed hydrodynamics, they are all limited in scope. In order to better understand the full scale of the effects that probes have on the hydrodynamics of fluidized beds, it is necessary to obtain data from a variety of locations within the bed. X-ray computed tomography allows for the time-average gas holdup to be calculated for the entire bed at the required resolution in order to assess the full effect of inserted probes. The goal of this study is to use X-ray computed tomography to assess the total effect, both locally and globally, of simulated measurement probes inserted into a fluidized bed reactor.

2. Experimental Setup

2.1 Fluidized Bed Reactor

A 3D cold flow fluidized bed reactor, very similar to the one used by Escudero and Heindel [24], was used in this study. The reactor was fabricated from clear acrylic with an

internal diameter of 10.2 cm and a wall thickness of 0.64 cm. Figure 1 shows the reactor with its four main parts: the plenum, aeration plate, bed chamber, and top chamber.

The fluidizing gas used for this research was compressed air which was supplied from the laboratory's building air supply. To initially regulate the air flow, a manual stainless steel pressure regulator with a pressure range of 0 to 689 kPa (0-100 psi) was used. The air was then directed through an Aalborg SMV40-SVF2-A stepper motor valve so that the flow rate could be automatically controlled. The air then passed through a 0-1000 Lpm stainless steel Aalborg GFM771 flow meter. Before the air was directed into the bed through an air inlet located at the bottom of the plenum, it first passed through a humidifier to minimize the electrostatic effects often found in fluidized beds. The plenum was filled to just below the aeration plate with 1.3 cm marbles to distribute the air from the inlet and to help ensure an even pressure distribution below the aeration plate.

Pressure within the bed was measured using a Dwyer 0-34.5 kPa (0-5 psig), 4-20 mA output pressure transducer located at the bottom of the plenum. A computer controlled data acquisition system was used to monitor the signals received both from the mass flow meter and pressure transducer. This system also served to control the average flow rate flowing into the fluidized bed.

The aeration plate was located above the plenum and immediately below the bed material chamber, and was composed of a 1.27 cm thick acrylic plate with 62 1-mm diameter holes. The holes were spaced roughly 1.27 cm apart in a circular grid for a total open area ratio of 0.62%. A number 45 wire mesh screen was secured on top of the aeration plate using silicon adhesive to prevent the material from obstructing the holes in the aeration plate.

The bed chamber was 61 cm tall and housed the fluidized material; it included a boss along the outside of the bed wall with five holes aligned vertically to accommodate the probe inserts used in this study, which simulated measurement probes. Six different probe geometries were tested and are shown in Figure 2. They are all fabricated from 3.2 mm diameter acrylic rods similar in diameter to those used by Rowe and Everett [20] and were bent and machined to obtain the shapes and dimensions shown. Three different probe tips were investigated: flat tip, pointed or needle tip, and round tip. Two different orientations were studied: horizontal and vertical. Vertical probes will vibrate if they are overly long and not secured near the probe tip. To alleviate this, the vertical probes used in this study were L-shaped and inserted through the side of the bed. Although a portion of the vertical probe was horizontal, this study focused on the hydrodynamic effects near the probe tip, and the horizontal portion of the vertical probe was located well above the probe tip. Individual probes were secured in place with two nylon set screws at the desired test height. These probes were each positioned within the fluidized bed so that the tip of the probe was aligned with the central axis of the reactor chamber. Four probe tip locations were tested: $h/D = 0.25, 0.5, 0.75$, and 1.0 , where h is the height of each probe tip from the aeration plate and D is the bed diameter.

To prevent the material from exiting the bed, each of the unused tap holes were plugged with short acrylic rods of the same diameter such that they were flush with the inner wall of the reactor chamber. These plugs were secured using the same nylon set screws. A top chamber was also included during the study to prevent particle elutriation.

2.2 Bed Material

The fluidized bed material used in this study was glass beads with a particle size range of 500-600 μm , which are classified as a Geldart type B particles [25]. The size range was obtained

by sieving the material multiple times with the aid of a mechanical shaker. The particle density of the glass beads was measured with a pycnometer to be 2510 kg/m^3 . The height of the static bed (H) was held constant for all conditions and was set at $H/D = 1$.

2.3 Minimum Fluidization Velocity

The minimum fluidization velocity (U_{mf}) was determined to provide a baseline for the two different superficial gas velocities used in this study, $U_g = 1.5U_{mf}$ and $3U_{mf}$. Using a computer controlled data acquisition system, the bed pressure drop was recorded and measured. To find the pressure drop, the bed material at the test height of $H/D = 1$ was fully fluidized with a superficial gas velocity much higher than the U_{mf} (e.g., $U_g = 35 \text{ cm/s}$). The superficial gas velocity was then incrementally decreased by 1 cm/s , pausing to ensure steady-state conditions, until it reached zero. The pressure readings were taken at each set velocity and recorded. The pressure was also recorded through an empty bed using the same procedure. These readings were used to calculate the pressure drop within the bed. Following the procedure of others [24], U_{mf} was determined. For statistical purposes, the U_{mf} test was completed five times and the values averaged together to obtain a value of $U_{mf} = 14.6 \text{ cm/s}$ when no probes were present.

It has been shown that single inserts have no effect on U_{mf} [19], but multiple inserts do have an effect on U_{mf} [26]; hence, the U_{mf} was determined for conditions with and without probes inserted into the bed. It was found that at a probe height of $h/D = 0.25$, there was no statistically significant difference found between U_{mf} at the no probe condition or with any of the six different inserted probes. The flat horizontal probe was then used to test the other three heights ($h/D = 0.5, 0.75, 1.0$) to ensure probe height did not influence the U_{mf} . No differences were observed and U_{mf} was concluded to be $U_{mf} = 14.6 \text{ cm/s}$ for all conditions used in this study.

2.4 X-ray computed tomography

Only a brief summary of the X-ray CT system used in this study is provided here because it has been detailed by Heindel et al. [27]. The X-ray source is a liquid cooled LORAD LPX200 which emits a conical X-ray beam. The maximum power output is 900 W, with a voltage range that can be adjusted from 10 to 200 keV and a current range from 0.1 to 10 mA. The power settings used for this study were set to 150 keV and 3.2 mA.

The X-ray detector used for CT imaging consisted of a 44×44 cm CsI phosphor screen. The images were captured by a thermoelectrically cooled Apogee Alta U9 CCD camera with a 50 mm Nikon lens. The cooling, along with long exposure time, reduced the noise in the obtained images. For this study, the camera was cooled to 0°C with an exposure time of 1 s for each image. The images were acquired using 4×4 camera binning, resulting in 768×512 effective pixels. An image, or X-ray projection, was acquired at each degree, 360° around the fluidized bed reactor. These images were then processed to take into account the different X-ray attenuation of the materials used as well as the individual variations between pixel readings in the detector and the camera [3, 27]. The 360 individual projections were then reconstructed to create a 3D intensity map of the fluidized bed. Note that it takes several minutes to acquire the 360 images and the resulting 3D intensity map is time-averaged. Drake and Heindel [6] have shown that the time-average CT images of a fluidized bed are highly repeatable; hence, it was assumed that the images in this study are a good representation of the time-average hydrodynamic conditions.

2.5 Gas Holdup

The gas holdup, also called the void fraction or volumetric gas fraction, quantifies the amount of voidage within the fluidized bed. Use of the X-ray CT system allows the time-average

gas holdup, ε_g , to be calculated based on the intensity values of the empty reactor chamber (I_g), the intensity values of a filled static bed (I_b), and the time-average intensity values of the flow condition (I_f). This necessitates that a full X-ray CT test be taken for an empty reactor chamber and for a bulk or static reactor at every probe condition in addition to the fluidized conditions. This allows the local time-average gas-holdup to be determined [3, 5]:

$$\varepsilon_g = \frac{I_f - I_b + (I_g - I_f)\varepsilon_{g,b}}{(I_g - I_b)} \quad (1)$$

where $\varepsilon_{g,b}$ is the bulk void fraction which is calculated by:

$$\varepsilon_{g,b} = 1 - \frac{\rho_b}{\rho_p} \quad (2)$$

and ρ_b and ρ_p are the bulk and particle density, respectively. The resulting 3D gas holdup image was analyzed along the different slice planes as shown in Figure 3. Each voxel, or 3D pixel, within the image contains the time-average gas holdup value of that location, and each voxel is $1.2 \times 1.2 \times 0.5$ mm ($x \times y \times z$). It is worth noting that because the probes were included in each of the three conditions necessary for calculating the gas holdup, the probe is subtracted out of the final gas holdup calculations.

3. Results and Discussion

The time-average gas holdup data obtained in this study allows for both local as well as global gas holdup analysis. Even though the initial U_{mf} tests indicated that probe effects did not alter U_{mf} , which could be influenced by large-scale hydrodynamic changes, local (or regional) gas holdup values may be different when probes are inserted into a fluidized bed. Specifically of interest in this study were the scale of the probe effects among the different probe tips and orientations when inserted at different bed heights of a fluidized bed operating at two different flow rates.

First, qualitative analysis of the gas holdup images was completed by applying a false color scheme to the grey-scale gas holdup images. The false color scheme that was applied in order to show better contrast is shown in Figures 4 and 5 for the horizontal and vertical probes, respectively, for $U_g = 3U_{mf}$. The first thing to note in Figure 4 is that the location of the horizontal probe at $h/D = 0.5$ is shown by the black line representing the respective probe in the Y- and Z-slice images (see Figure 3). The black dot in the X-slice images identifies the probe tip. The gas holdup values near the probe are slightly higher than the condition with no probes. Even at the tip of the probe (X-slice), where the measurement would take place, the gas holdup values are higher suggesting that any local probe measurements could be altered and confirming the results of Dubrawski et al. [23]. However, even though there is a discernible difference near where the probe is located, there doesn't appear to be a difference on the overall gas holdup values throughout the bed. In the Y-slice of the horizontal needle probe, there is a slightly lower gas holdup value found just above where the probe is located, indicating a higher percentage of particles at that location compared to the no probe condition. The probe may cause the particles to become trapped on the probe upper region by blocking the rising fluidization gas from reaching the particles. In contrast, the round and flat tip conditions show a slightly elevated gas holdup near the upper region of the probe shaft, indicating a small gas pocket has formed. Some conditions show a lower gas holdup on the upper probe region, while others show higher gas holdup values, but there are no discernible trends either among the different tip geometries, gas flow rates, or probe axial locations.

Figure 5 shows the three vertical probes inserted such that the probe tip was located at $h/D = 0.25$ with $U_g = 3U_{mf}$. Note that the horizontal sections of the vertical probes are located $1/4D$ above the probe tip (2.54 cm), which places this section at $h/D = 0.5$ in Figure 5. Again, the

location of the probe is represented by the black insert at the correct locations. The gas holdup appears to be slightly elevated near the probe geometry. The needle tip shows a less prominent increase right at the tip (see Z-slice images), most likely due to the smaller tip geometry at the location of the image. In the X- and Y-slice, the gas holdup is slightly higher along the vertical portion of the probe, confirming the observations of Rowe and Masson [21]. Another interesting feature that Figure 5 illustrates is that there is a slight decrease in gas holdup values in the area just outside of the probe geometry. This implies that the local gas migrated toward the vertical probe region, leaving adjacent regions slightly deficient of gas.

Based on the color contour maps, the most significant effect of the simulated probes is on the gas holdup values in the immediate vicinity of the probes, defined as the region encompassing approximately one probe diameter away from the probe surface.

Global probe effects were determined by observing the horizontal average gas holdup as a function of bed height, which was determined by averaging the local gas holdup values along a given Z-slice. For each probe tip located at $h/D = 0.5$ and $U_g = 3U_{mf}$, as shown in Figure 6, the horizontal average gas holdup values are largely unaffected by probe inserts, correlating with what was observed in Figures 4 and 5. The gas holdup values follow the same trends above and below the probe location when compared to the no probe case. There is, however, small variations at $h/D = 0.5$ where the probe tip is located, suggesting a localized effect of the probes, but the effect is minimal. Similar results were observed in all other studied conditions. There was little deviation above and below the probes and the only small deviations occurred where the probes were located. Due to system constraints, the vertically oriented probes were only vertical for a limited height and there were multiple instances where the larger variations for vertical probes occurred at the bend rather than simply at the probe tip (e.g., Figure 2). From this it seems

as though the effects of the horizontal portions of the vertical probes have a larger influence than the vertical portions, which is consistent with previous studies [20, 21]. Also note in Figure 6 that the overall bed expansion height is unaffected by the presence of the probe inserts.

Figure 7a shows local gas holdup values along a ray in the X-slice (see Figure 3) through the bed centerline for the three different horizontal probes inserted at a height of $h/D = 0.5$ at $U_g = 1.5U_{mf}$, while Figure 7b shows the same axial location along the Y-slice (i.e., a ray through the bed centerline at the same axial location but perpendicular to the one in Figure 7a). The diagrams in the upper left hand corner of each plot illustrate the orientation and location of the probes for the given plot, while the dotted line in each diagram indicate at which axial height the local gas holdup values correspond; in Figure 7, it is at an axial location directly above the probe ($h/D = 0.53$) to avoid the inconclusive data obtained where the probe is subtracted out in the local gas holdup calculation (Eqn. (1)). This study also looked at the data directly below the probes, but generally there was not much effect below the probes; therefore, the results presented here focus mainly on the local gas holdup values above the probes. Hence, the data in Figure 7 are local values along a ray through the center of the bed in the given X- and Y-slice at the specified axial (h) location.

Figure 7a shows that there is an increase in the gas holdup values for each of the probes at this location compared to the no probe condition. The increase is not limited to just the tip of the probes, but rather is distributed across much of the horizontal plane. The three different tip geometries exhibit differences in the scale of local gas holdup increase with the flat geometry showing the most effect, followed by the round geometry, and then needle geometry which exhibits almost no effects. The condition in Figure 7a is a worse-case result and other test conditions show inconsistent trends; in fact, most cases show no significant differences between

the three different tip geometries. Figure 7b also shows an increase in gas holdup values when probes are inserted, but the increase is asymmetric and is larger where the probe tip is located. The gas holdup increases along the entire length of the probe inferring that the fluidizing gas encompasses the probes, which is consistent with previous work [20] and qualitative analysis of the gas holdup maps (e.g., Figure 4). There is also a small spike in the gas holdup values at the probe tip. The slight flexibility of the probes may have allowed for the horizontal probe to bend upwards towards the middle and allow for flow up and along its length. Similar results were observed for all of the horizontal probes, although the scale of the effects was largely dependent upon the height at which the probes were inserted. The difference in tip geometries is not observed in the Y-slice viewing plane and the inserts all follow the same trend.

In general, as shown in Figure 8, the lower that the probes were inserted into the bed, the larger the increase in the gas holdup immediately surrounding the probe tips. This local increase around the probe can be up to ~50% higher than the no probe condition when the horizontal probe is inserted at $h/D = 0.25$. At the lower heights ($h/D = 0.25, 0.5$), the gas holdup increase is large along the probe length directly above the probe. The higher height of $h/D = 0.75$ shows much less effect, and in fact, the increase in gas holdup is minimal at this location and condition. This result may be due to the jetting effect caused by the aeration plate that is still present at $h/D = 0.25$, and which can be seen in Figures 4 and 5. Jetting in the aeration region was also noted by Drake and Heindel [6] and quantified by Escudero and Heindel [28]. By the time the fluidization gas reaches $h/D = 0.75$, there is a lot more uniformity within the bed, leading to smaller probe effects. Near the bed surface ($h/D = 1.0$), probe effects increase; this results in the higher local gas holdup values observed at $h/D = 1.0$ which are comparable in magnitude to the results seen at $h/D = 0.5$. Hence, when the local bed hydrodynamics are influenced near the aeration region

or bed surface, local horizontal probes have a larger effect on the local gas holdup, but when the probes are located in the bed bulk, the probe influence is suppressed.

Figure 9 shows the local gas holdup along an X-slice for the three different tips using vertical probes with the probe tips positioned at $h/D = 0.25$. This plane shows the vertical section of the probe while the horizontal probe portion (see Figure 2) extends out of the viewing plane. The data omitted at $h/D = 0.375$ correspond to where the probe is located, and it is omitted because the insert creates an inaccurate local gas holdup calculation in the probe region. When $U_g = 1.5U_{mf}$, as shown in Figure 9a, there is a minimal disturbance caused by the probes near the tip location ($h/D = 0.22$). Near $r/R = 0$ and $h/D = 0.375$, there is an increase in gas holdup values directly surrounding the probe. This infers that a central spout is present as the gas travels up the vertical shaft. When $U_g = 3U_{mf}$, the effects at the probe tip are more apparent. The decrease in the middle of Figure 9b when $h/D = 0.22$ occurs right where the probe tip is located. This is most likely due to the insert and drawing the gas from the immediate vicinity and moving it more quickly up along the probe shaft. The tendency for a slight gas holdup decrease right below the probe tip was seen exclusively with the vertical probe orientation and was more prevalent at $U_g = 3U_{mf}$, but was also observed at $U_g = 1.5U_{mf}$ for some probe axial positions.

Also of note in Figure 9 is the gas holdup decrease directly on either side of where the probes are located. The overall shape of this curve indicates that the probe attracts the nearby fluidizing gas and acts as a spouting agent for the gas. This effect extends up the length of the vertical probes as Figures 9a and 9b show at $h/D = 0.375$. The probe effects appear to be localized so the average gas holdup values for the bed are unaffected (see Figure 6), although the local flow conditions within the bed are considerably altered.

Figure 10 shows the Y-slice planes for the same conditions as in Figure 9. For $U_g = 1.5U_{mf}$, there is an increase in the gas holdup value at the probe tips, as well as to the right of the probe tip, which corresponds to the area of the probe beneath the bend between the vertical and horizontal components of the probes (see Figure 5). The difference between the probe and no probe results is larger at the lower gas flow rate (Figure 10a), but it is still significant at $U_g = 3U_{mf}$. Similar results were observed when the same probes were located at different bed heights. This contrasts with the results in Figure 9 where larger effects are seen at the higher flow rate for the same experimental data set, except that they were evaluated along a different plane. From this it can be seen that the flow rate and location relative to the probe are factors in the scale of the probe effects.

Figures 9 and 10 both show that the probe effect located at the bend in the vertical probes (see Figure 5) is also significant. Where the bend occurs ($h/D = 0.5$ in Figures 9 and 10), there is a large increase in the gas holdup values. Above this point the effects begin to appear similar to that of the horizontal probe inserts (compare with Figure 8). This indicates that the horizontal portion of the vertical probe produces the more prominent effect on the gas holdup increase.

Figure 11 shows one example of the differences observed between the two probe orientations. It illustrates the larger effects that are caused by the horizontal probe orientation versus the vertical probe orientation. There is only a small gas holdup increase at the tip of the vertical probe, whereas the horizontal probe shows a much more distributed effect across the fluidized bed. This makes sense when thought of in terms of the blockage ratio [19] where the larger the blockage ratio, the larger the corresponding changes are in the hydrodynamic structure of the fluidized bed. The horizontal probes have a larger blockage ratio at the probe tip height when compared to the vertical probe inserts. However, this is only true at locations below the

bend in the vertical probes. The vertical probes exhibit increases in gas holdup values similar in magnitude to the horizontal probes immediately above the height of the bend.

Another observation made during this study was the effect of simply adding the five different probe inlets along the wall of the fluidized bed. Although this was not explicitly tested against any other condition, it was noted that the no probe condition with no inserts had a slight increase in gas holdup in the Y-plane along the wall where probe inlet holes are located (e.g., Figure 7b). Previous studies using the same reactor before the inlet holes were added show that this particular wall effect was not always present [9, 29]. Although the probe inlet holes were plugged with blank inserts that were flush-mounted to the walls as best as possible, there are still small discontinuities at the inlet hole locations. If this wall effect is indeed caused by the inclusion of the plugs, as it seems to be, this could have ramifications for measurement techniques that use devices that are flush with the interior reactor wall, such as pressure transducers. Similar observations were made by Drake and Heindel [6].

4. Conclusions

For the conditions of this study, there was minimal effect from the probe inserts on the overall average gas holdup values in a fluidized bed. There were, however, significant local variations in the gas holdup value both at the probe tips and even in the flow above the inserts. The lower the probes were inserted in the bed, the larger the observed influence, particularly when the probes were inserted into the aeration region. Apart from a select few conditions, the different probe tip geometries did not provide different effects, but horizontal probes were more influential to the local hydrodynamics than vertical probes. The most important factors on the probe effect on local gas holdup were observed to be the probe axial location within the bed and the flow rate of the fluidizing material. Therefore, to minimize the effects that probes have on the

local hydrodynamics of the bed, it is suggested that the probes be placed outside the aeration region where individual aeration jets are present, but below the height where surface effects begin, the superficial gas velocity should be well above the minimum fluidization velocity, and the probe orientation should be vertical.

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7a

Figure 7b

Figure 8

Figure 9a

Figure 9b

Figure 10a

Figure 10b

Figure 11