



*Institute of Paper Science and Technology
Atlanta, Georgia*

IPST Technical Paper Series Number 731

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June 1998

**Submitted to
1998 TAPPI Engineering Conference
Miami Beach, FL
September 13–17**

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A STUDY OF GAS HOLDUP IN A COCURRENT AIR/WATER/FIBER SYSTEM

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ABSTRACT

Gas/liquid/fiber flows occur in many places in the pulp and paper industry, such as flotation deinking, bleaching with gaseous chemicals, direct contact steam heating, and air removal from stock flows. However, little is known about the dynamics of these complex flows. In this study, the gas holdup of an air/water/wood pulp suspension was characterized to determine the effects of varying pulp consistency and superficial gas (air) and liquid (pulp) velocities, where the superficial velocity is defined as the volumetric flowrate divided by the column cross-sectional area. The study focused on measuring gas holdup (percent air by volume) through pulp stock consisting of unprinted old newspaper (ONP) in a 12.7 cm diameter cocurrent bubble column. The gas holdup was measured by gamma-ray densitometry, and chord-averaged gas holdup values were determined at various chord positions across specified planes at multiple column heights. Pulp consistency was specified at one of three values (0, 0.8, and 1.2%), the superficial gas velocity was varied between 0.5 and 4.0 cm/s, and the superficial liquid velocity was varied between 2.5 and 7.5 cm/s. These parameters were chosen to most accurately resemble those of flotation deinking cells in the pulp and paper industry.

It was found that gas holdup generally increases with increasing column height, superficial gas velocity, and superficial liquid velocity, for each consistency studied. The effect of pulp consistency on gas holdup was dependent upon superficial gas and liquid velocities. Pulp fibers at 0.8% consistency caused the gas holdup to increase relative to pure water at high superficial liquid velocities. This was caused by a reduction in bubble coalescence due to the movement of the slurry and the fiber network. As pulp consistency increased to 1.2%, the gas holdup decreased below that of pure water. This decrease is thought to be due to channeling at high consistencies. Additionally, at low superficial liquid velocities, the gas holdup decreased as consistency increased, which is thought to be due to bubble coalescence and channeling.

INTRODUCTION

Gas/liquid/fiber flows are common in the pulp and paper industry, but little information is known about the characteristics of these complex flows. Flotation deinking, bleaching with gaseous chemicals, direct contact steam heating, and air removal from stock flows would all benefit from knowledge of these flow characteristics, such as bubble size, bubble rise velocity, gas holdup, flow regime, etc. This study records chord-average gas holdup values for a variety of flow conditions in an air/water/fiber cocurrent bubble column. The chord-average values are used to calculate cross-sectional average gas holdup values, and the effects of column height, superficial gas and liquid velocity, and fiber consistency are determined. Here, the superficial velocity represents the effective liquid or gas velocity in the column if only one constituent is present and is defined as the liquid or gas volumetric flowrate divided by the column cross-sectional area.

In flotation deinking, aeration ratios of 200-1000% have been reported [1]. This value is defined as the total volumetric gas flowrate compared to the total volumetric slurry flowrate, and is easily controlled or altered by adjusting either (or both) flowrates. However, these values do not necessarily correlate to effective flotation cell operation. Gas holdup (or void volume or void fraction), defined as the percent gas volume in a multiphase system, may be a more appropriate measure for flotation cell performance. Gas holdup may be influenced by the flow conditions, flow geometry, fluid properties, and fiber consistency, and is typically spatially dependent [2-5]. Typical flotation cells operate with a gas holdup on the order of 10-20% [6]. However, a high gas holdup is not necessarily better. For example, annular flow conditions, in which the gas flow is confined to the central portion of the column

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and the liquid flows in an annulus near the column walls, could produce a very high gas holdup (or void fraction), but would not lead to effective flotation deinking. A uniform gas holdup created by bubbly flow conditions would be more desirable in a flotation cell because the air being introduced into the system would be uniformly distributed. In general, to identify optimum operating conditions, the magnitude and distribution of gas holdup in a cell would be needed, with a high but uniformly distributed value being most desirable.

Gas flow characteristics in flotation deinking cells are primarily bubbly or churn-turbulent. Bubbly flow is characterized by an even distribution of many small bubbles with minor interactions between the bubbles, rising in a continuous liquid phase. In gas/liquid bubble columns, bubbly flow is usually assumed to occur at superficial gas velocities below 5 cm/s [7]. Flotation deinking cells operate in this range of superficial gas velocities [1]. As the superficial gas velocity increases, bubbles coalesce to form larger bubbles, which rise at a faster rate due to the increased buoyant force associated with the larger bubbles. These fast rising bubbles cause turbulence from vortex shedding in the wake of the bubble. This flow regime is generally called churn-turbulent and is associated with superficial gas velocities as high as 10-15 cm/s [7]. Slug, annular, and dispersed annular flow regimes occur at even higher superficial gas velocities and are typically found in narrow diameter bubble columns [4, 8]. These latter flow conditions are generally not found in typical flotation deinking equipment.

A crucial parameter in bubble column operation is gas holdup. A high gas holdup often implies an increase in the total interfacial area between a gas and liquid and/or an increase in the gas residence time, both of which lead to higher transfer rates [6]. Gas holdup increases with increasing superficial gas velocity when the flow is bubbly. However, when gas bubbles coalesce, the gas holdup is reduced because larger bubbles rise faster than smaller ones [2, 9, 10]. This trend was also observed by De Swart et al. [11] and Krishna et al. [5] for slurry flows. As cited by Wallis [12], Zuber and Hensch [13] have shown that churn-turbulent flow conditions reduce gas holdup, but these results were a function of how the air was introduced into a quiescent bubble column (a batch process or no bulk fluid flow – a superficial liquid velocity of zero). This trend was also observed by Michelsen and Østergaard [14] in fluidized beds.

Backmixing or flow recirculation, where fluid flows in the opposite direction of the bulk flow, is also a factor in bubble column design and operation. In upflow bubble columns, the bulk flow (liquid and air) generally travels through the column center. The upward movement of the bulk flow may cause some downward movement of the liquid along the column walls. The magnitude of backmixing or recirculation is dependent upon the superficial gas velocity and the column diameter. Low superficial gas velocities generally show little backmixing while high superficial gas velocities show intense backmixing. Additionally, smaller diameter columns inhibit backmixing [8, 12]. The degree of backmixing is also influenced by the type of gas bubbles present in the bubble column. In the churn-turbulent bubble regime, Krishna et al. [5] divided the flow into a “dilute” and “dense” phase for slurry bubble columns. The dilute phase was identified with fast-rising “large” bubbles which traverse the bubble column virtually in plug flow. In contrast, the dense phase was identified with the liquid phase and solid particles with entrained “small” bubbles. They concluded that the dense phase suffers a considerable degree of backmixing. They also recorded gas holdup for each phase and determined that even though increasing the solids concentration decreased the overall gas holdup, the effect on the dilute phase was small. However, a considerable decrease in the dense phase gas holdup was observed and was attributed to the enhanced coalescence of small bubbles with increasing solids content.

Gas/water/fiber flows in pulp and paper processing are complex slurry flows because the fibers have a density close to that of water and they can form flocs at consistencies as low as 0.3% by weight, and continuous fiber networks at consistencies greater than 1% [15]. Walmsley [16] reported gas holdup values for a quiescent fiber system consisting of clove oil or water and mechanical or chemical wood pulp fibers. Gas holdup was recorded by observing the bed expansion (change in column height) when air was introduced. Both mechanical and chemical wood pulp fibers decreased the gas holdup when the consistency was greater than 0.6%. Walmsley concluded that the decrease in gas holdup implies an increase in bubble coalescence and/or channeling, which will lead to a reduction in the overall air/liquid interfacial area.

Using a quiescent rectangular bubble column, Reese et al. [17] concluded that the hydrodynamic behavior of a three-phase fibrous slurry deviates from the behavior of a simple gas/liquid system, even at fiber consistencies as low as 0.1%. The presence of pulp fibers increased bubble coalescence and reduced the overall gas holdup compared to an air/water system at the same superficial gas velocity. The larger bubbles also increased the turbulence in the system and the degree of backmixing in the column.

Lindsay and co-workers [6, 18-21] measured gas holdup in a cylindrical quiescent bubble column filled with 0, 1, and 2% ONP fiber suspensions and a cocurrent bubble column filled with either 0 or 1% ONP fiber suspensions. In the quiescent bubble column, gas holdup values were less uniform and lower in the fiber systems, implying gas channeling and lower gas residency time in the suspension. Both conditions are detrimental to effective flotation deinking. In the cocurrent bubble column, the 1% fiber suspension had a higher gas holdup than that recorded for the water system, and the gas holdup increased when the superficial liquid velocity exceeded the superficial gas velocity.

In this study, gas holdup was measured in a cocurrent bubble column filled with various consistencies of a cellulose fiber suspension. Chord-average gas holdup values were recorded at various lateral and vertical locations using gamma-ray densitometry. Parameters of interest include superficial gas velocity ($0.5 \text{ cm/s} \leq v_g \leq 4.0 \text{ cm/s}$), superficial liquid velocity ($2.5 \text{ cm/s} \leq v_l \leq 7.5 \text{ cm/s}$), and fiber consistency ($0\% \leq C \leq 1.2\%$).

EXPERIMENTAL METHODS

Gas holdup measurements in a vertical cocurrent bubble column filled with a fibrous slurry were obtained in this study. The fibrous slurry consisted of unprinted old newspaper (ONP) mixed with tap water. Three consistencies (C) were addressed in this study and include $C = 0\%$ (corresponding to an air/water system), 0.8%, and 1.2%. This consistency range corresponds to that typically encountered in flotation deinking operations.

A schematic of the experimental system used in this study, which is very similar to that used by George [19] and Lindsay et al. [6], is shown in Fig. 1. The gas holdup measurements were obtained in the vertical bubble column, which consisted of a 1.5 m long transparent acrylic column with an internal diameter of 12.7 cm. Pulp flowrates were monitored with a Krohne magnetic flowmeter and encompassed a range of 19 to 57 lpm (liters per minute) (5-15 gpm). In multiphase flow studies, superficial velocities are commonly reported and correspond to the effective velocity if only one constituent is present. This velocity is defined as the liquid (or gas) volumetric flowrate divided by the column cross-sectional area. In this study, the water/fiber mixture is assumed to be a single component and is identified as the liquid. Therefore, the superficial liquid velocity range addressed in this study is $2.5 \text{ cm/s} \leq v_l \leq 7.5 \text{ cm/s}$.

The gas used in this study was compressed and filtered building air. Pressurized air was injected into the flowing slurry in a 2.5 cm diameter tube prior to a conical diffuser at the column base. Gas dispersion was caused by high shear conditions in the 2.5 cm tube, where the liquid Reynolds number, based on water properties, ranged from 1.6×10^4 to 4.8×10^4 for the conditions of this study. Air was introduced under pressure to allow for air flowrate control (as opposed to a venturi injector, where the gas flowrate is a function of the liquid flowrate). Volumetric air flowrates were measured with a Hastings mass flowmeter and ranged from 3.78 to 30.4 lpm (1-8 gpm), corresponding to a superficial gas velocity range of $0.5 \text{ cm/s} \leq v_g \leq 4.0 \text{ cm/s}$ and is typical of that found in flotation deinking cells [1].

A conical constriction at the top of the bubble column channeled the air/water/fiber mixture from the column into a 2.5 cm diameter tube, which transitions into an 8 cm diameter pipe. This pipe formed a "T" section with one end open to the atmosphere to allow for air to escape and prevent siphoning, and the other end expelled the water/fiber mixture, with any remaining air, into the first of two consecutive holding tanks. It was assumed that these consecutive tanks provided sufficient time for any entrained air to be expelled from the system. Since dilute cellulose fiber suspensions have the propensity to separate after an extended time period, the fiber slurry was gently agitated by a Lightnin mixer in each tank to maintain the fiber consistency at a constant value. The water/fiber slurry was then returned to the test section by a Diskflo pump.

Gas holdup in a multiphase system can be recorded with a variety of methods, including measuring the increase in column height when the gas is introduced [6, 17, 22], dynamic gas disengagement [5, 23], pressure drop measurements [22, 24, 25], electric resistivity probes [26-29], ultrasonics [30, 31], computed tomographic (CT) scans [3], and gamma-ray densitometry [6, 18-21, 27, 32, 33]. Gamma-ray densitometry is a radiation technique in which the attenuation of a gamma-ray beam, caused by mass interference between a gamma-ray source and detector, is recorded and correlated to the chord-average gas holdup value. Details of this technique can be found in [6, 27, 32-34]. This latter technique was utilized in this study.

The gas holdup measurements were obtained with a gamma-ray densitometer consisting of a 45 mCi Americium-241 gamma-ray source and an Ortec gamma-ray detector. The bubble column was located between the gamma-ray

source and detector, which were aligned and mounted on a horizontal and vertical traversing mechanism. This allowed for chord-average gas holdup measurements at various lateral and vertical locations. Table 1 summarizes the bubble column locations used in this study to obtain chord-average gas holdup values and the corresponding chord lengths.

Table 1: Lateral and vertical locations for chord-average gas holdup measurements in this study.

| Lateral distance from the column centerline. | Chord length at given lateral location. | Vertical distance above the conical diffuser outlet. |
|--|---|--|
| -5.72 cm | 5.52 cm | 30.5 cm |
| -4.45 cm | 9.06 cm | 50.8 cm |
| -3.18 cm | 10.99 cm | 71.1 cm |
| -1.91 cm | 12.11 cm | 91.4 cm |
| -0.64 cm | 12.64 cm | 111.8 cm |
| 0.0 cm | 12.70 cm | 132.1 cm |
| 1.27 cm | 12.44 cm | |
| 2.54 cm | 11.64 cm | |
| 3.81 cm | 10.16 cm | |
| 5.08 cm | 7.62 cm | |

The chord-average gas holdup, $\varepsilon_{i,j}$, is obtained by gamma-ray densitometry from [27]

$$\varepsilon_{i,j} = \frac{\ln(I_{i,j} / I_{i,j}^f)}{\ln(I_{i,j}^g / I_{i,j}^f)} \quad (1)$$

where $I_{i,j}$ is the number of incident gamma-ray counts during a data collection cycle, $I_{i,j}^f$ and $I_{i,j}^g$ are the number of incident gamma-ray counts for the all-liquid and all-gas conditions, respectively, and the subscripts i and j represent the lateral and vertical location of each chord. The $I_{i,j}^f$ and $I_{i,j}^g$ values were obtained through calibration before an experiment was initiated. Gamma-ray counts must be obtained over a given time interval to accurately record the chord-average gas holdup. For all test conditions, as well as the calibration conditions, gamma-ray counts were obtained over a 10 second interval. This was repeated 10 times and the average count for each test condition was used in Eq. (1) to determine the chord-average gas holdup. Therefore, the gas holdup values measured in this study by gamma-ray densitometry are time-averaged, as well as chord-averaged.

To obtain chord-average gas holdup values for each test condition, the column height location was initially fixed. The gamma-ray densitometer was then calibrated to account for background radiation effects by taking ten gamma-ray count readings, at ten seconds each, with the gamma-ray source aperture closed. (This calibration procedure was also performed after an experiment was completed.) The average gamma-ray counts from the background radiation calibration was then subtracted from the number of incident counts when the gamma-ray source aperture was open ($I_{i,j}$, $I_{i,j}^f$, and $I_{i,j}^g$). After the background radiation calibration, the gamma-ray source aperture was opened and ten gamma-ray count readings (at 10 seconds each) were taken of an empty column at each chord location to obtain the all-air calibration value ($I_{i,j}^g$). The column was then filled with a 0, 0.8, or 1.2% consistency ONP slurry and ten gamma-ray count readings (at 10 seconds each) were taken at each chord location to determine the all-liquid

calibration value ($I_{i,j}^f$). After these calibration readings, the gas and liquid flowrates were set to their desired values and ten gamma-ray count readings (at 10 seconds each) were recorded for each chord position ($I_{i,j}$). The gas and/or liquid flowrates were then adjusted to a new value and additional data were collected in a similar manner. During these experiments, background radiation calibration was performed at the initiation and termination of each testing period (typically one full day). The all-liquid and all-air calibrations were performed whenever the consistency or column height was changed. The chord-average gas holdup was then determined from the time-averaged gamma-ray count data using Eq. (1).

The chord-average gas holdup values are used to determine the cross-sectional average gas holdup defined by

$$\varepsilon_{H,j} = \frac{\sum_{i=1}^m \varepsilon_{i,j} \ell_i}{\sum_{i=1}^m \ell_i} \quad (2)$$

where $\varepsilon_{i,j}$ is the chord-average gas holdup determined from Eq. (1), ℓ_i is the length of chord i (Table 1), and m is the number of chords where gas holdup was measured ($m = 10$ in this study). Chord-average gas holdup measurements can be transformed to determine the radial gas holdup distribution [6, 32, 33], but unrealistic values can be produced if the chord-average values do not form a smooth function. Lindsay et al. [6] used a quadratic curve-fit to generate a smooth curve to obtain a radial gas holdup distribution from their chord-average values. Shollenberger et al. [33] used a fourth-order polynomial curve-fit with even powers in the lateral position to obtain smooth ray-averaged attenuation coefficients. Since the main focus of this study is a comparison of cross-sectional average gas holdup values, the transformation from chord-average gas holdup values to radial gas holdup distributions will not be presented here.

In a cocurrent bubble column, column-average gas holdup values can be estimated by dynamic gas disengagement techniques [5, 23] and pressure drop measurements [22, 24, 25]. In this study, column-average gas holdup values were obtained by averaging the cross-sectional average gas holdup:

$$\varepsilon_C = \frac{\sum_{j=1}^n \varepsilon_{H,j}}{n} \quad (3)$$

where $\varepsilon_{H,j}$ is the cross-sectional average gas holdup determined from Eq. (2) and n represents the number of height locations where cross-sectional average gas holdup values were determined ($n = 6$ in this study).

RESULTS

Gas holdup measurements were obtained in a cocurrent bubble column at various lateral and vertical column locations, superficial gas and liquid velocities, and ONP pulp consistencies. Results from these experiments are presented below.

A typical graph showing the relationship between gas holdup and chord location across a given bubble column height is shown in Fig. 2 for $v_g = 4$ cm/s, $v_L = 2.5$ cm/s, $H = 91.4$ cm, and $C = 0.8\%$. The column walls are located at ± 6.35 cm from the column centerline. Figure 2 shows that the gas holdup is higher in the center of the column than near the walls for the given test conditions. The gas holdup distribution shown in Fig. 2 is generally symmetric about the column centerline and is a typical representation of the results obtained for the conditions of this study. This distribution is also typical of that observed in other bubble columns [3, 6, 28, 33]. The higher gas holdup in the central region of the bubble column is due to the concentration of the gas phase near the column core [8], which will also promote bubble coalescence in this region. Extrapolating the gas holdup to the column walls (± 6.35 cm), the gas holdup does approach zero but may not be identically zero as expected [4]. This trend was also observed by Shollenberger et al. [33] and was attributed to the difficulty in obtaining accurate gas holdup measurements near the wall of a bubble column with gamma-ray densitometry. Note that this figure does not show gas holdup variations as a function of column radius; rather, gas holdup as a function of distance from the column

centerline to a particular chord location. As previously discussed, radial gas holdup distributions will not be presented here.

Effect of Column Height

The effect of column height on the cross-sectional average gas holdup is shown in Fig. 3 for $C = 0.8\%$ and $v_L = 2.5$ cm/s. At $v_g = 0.5$ cm/s, the cross-sectional average gas holdup is constant over the entire column height. At this superficial gas velocity, bubbly flow is observed and little, if any, backmixing is apparent. Increasing the superficial gas velocity to $v_g = 2.0$ cm/s reveals an increase in cross-sectional average gas holdup with increasing column height, which is due to backmixing near the column top. Air-rich pulp recirculates at the top of the column due, in part, to the conical constriction, and flows down the column walls while the bulk flow is in the column center. It actually appears to the observer that the pulp is traveling from top to bottom in this section of the column until one views the exit port at the top of the column, which clearly shows stock leaving the column. This backmixing (or recirculation) increases the cross-sectional average gas holdup from $\sim 4\%$ to $\sim 6\%$ as the height is increased from $H = 30.5$ cm to $H = 132.1$ cm.

The gas holdup gradient along the column height is larger when $v_g = 4.0$ cm/s. At this superficial gas velocity, more backmixing is observed and covers much more of the column height. The backmixed fluid (and entrained air) is eventually reentrained in the bulk upward flow. One observation from Fig. 3 is that the cross-sectional average gas holdup increases with increasing superficial gas velocity, while the superficial liquid velocity, column height, and consistency are held constant. This will be addressed in the following section. Finally, similar trends to those revealed in Fig. 3 are observed at other superficial liquid velocities and consistencies.

Effect of Superficial Gas Velocity

Typical chord-average gas holdup values for various superficial gas velocities are shown in Fig. 4 for $C = 0.8\%$, $v_L = 7.5$ cm/s, and $H = 50.8$ cm. In air/water quiescent bubble columns, the gas holdup distributions tend to be parabolic at high superficial gas velocities and tend to flatten out at lower superficial gas velocities [3]. This trend is also observed in this study and the trend lines in Fig. 4 represent quadratic distributions in chord-average gas holdup with distance from the column centerline. Some of the distributions are slightly asymmetric (i.e., $v_g = 1.0$ cm/s). This observation is not uncommon and has been reported by others [6, 35]. Finch et al. [36] report that gas holdup variations in the radial direction of a cocurrent bubble column may be influenced by the bubble generation system (e.g., the type and/or arrangement of spargers), the uniformity in the gas injection, the gas flowrate, and surface active agents that may be present in the fluid. The asymmetry observed in this study may be the result of nonuniform air injection at the column base. Also, the conical diffuser may also introduce oscillations that could contribute to asymmetric gas holdup values [35]. Increasing the superficial gas velocity increases the chord-average holdup because more air is dispersed in the fluid. This has been reported for simple air/water quiescent and cocurrent bubble columns [7, 9], as well as quiescent and cocurrent slurry flow bubble columns [2, 6].

The increase in gas holdup with increasing superficial gas velocity is clearly observed when cross-sectional average gas holdup values are determined for the conditions shown in Fig. 4. This result is presented in Fig. 5, which shows a linear relationship between superficial gas velocity and cross-sectional average gas holdup. Lindsay et al. [6] have also shown similar results. Extrapolating the linear best-fit line to $v_g = 0$ cm/s reveals that the cross-sectional average gas holdup is not zero, as one would expect. This was also observed by Lindsay et al. [6] and may be due to entrained air within the suspension not completely escaping while in the holding tanks. This phenomenon will be discussed in more detail below.

Effect of Superficial Liquid Velocity

Figure 6 shows the effect superficial liquid velocity has on cross-sectional average gas holdup at $H = 50.8$ cm for three superficial gas velocities ($v_g = 0.5, 2.0,$ and 4.0 cm/s) and three ONP fiber consistencies (0, 0.8, and 1.2%). As air is injected into a bubble column, the bubbles rise from the injector ports. If the bubbles are not removed fast enough, they coalesce with other bubbles forming larger bubbles with a corresponding larger buoyant force and faster rise velocity. These large, fast rising bubbles tend to reduce the gas holdup when compared to well-dispersed small bubbles produced at the same air flow rate. For a fixed air flow rate, if the liquid flow rate in the bubble column increases, the faster flowing fluid removes bubbles from the injector port at a faster rate, which keeps the bubbles small and well-dispersed, as well as increases the amount of backmixing observed in the system. This results in an

increase in the cross-sectional average gas holdup as the superficial velocity is increased. It is interesting to note that the consistency at which the maximum cross-sectional average gas holdup occurs depends on both the superficial liquid and gas velocities. This will be discussed in detail in the following section.

At the top of the bubble column, the previous trends are not always observed. As shown in Fig. 7 for $H = 132.1$ cm, cross-sectional average gas holdup increases with increasing superficial liquid velocity when $C = 0.8\%$ for $v_g = 0.5, 2.0$, and 4.0 cm/s. However, when $C = 0$ and 1.2% , the cross-sectional average gas holdup either remains approximately constant or decreases with increasing v_L . This observation was unexpected and is not completely understood. One possible explanation is that at the higher superficial liquid velocities, the liquid momentum reduces the amount of backmixing and/or gas caught in the backmixed region at this column height. Kelkar et al. [2] report a nonlinear effect of superficial liquid velocity on gas holdup for a cocurrent system containing 10% (by weight) of polystyrene beads. They attribute this result to the slip between the phases. When $v_g \leq v_L$, the slip between the phases becomes dependent on the liquid velocity, and hence affects gas holdup. As the superficial gas velocity increases, churn-turbulent flow conditions are encountered and the influence of superficial liquid velocity is less predominant. As shown in Fig. 7, this complex relation also appears to be a function of fiber consistency. More research is required in this area to completely address this phenomenon.

Effect of ONP Consistency

A typical result of chord-average gas holdup at three different ONP consistencies is shown in Fig. 8, which was generated with $v_g = 4.0$ cm/s, $v_L = 7.5$ cm/s, and $H = 50.8$ cm. A general parabolic shape in the chord-average gas holdup is obtained as a function of distance from the column centerline. The parabolic trend lines also show slight asymmetry in the results, with the $C = 0\%$ (i.e., the air/water system) showing the most asymmetry. This figure also reveals that for these conditions, the maximum chord-average gas holdup at all chord locations occurs when the ONP consistency is $C = 0.8\%$ and a minimum results when $C = 1.2\%$.

Figure 9 shows the cross-sectional average gas holdup values as a function of ONP consistency for all superficial liquid velocities considered in this study (i.e., $v_L = 2.5, 5.0$, and 7.5 cm/s), two superficial gas velocities of $v_g = 0.5$ and 4.0 cm/s, and a column height of $H = 50.8$ cm. When $v_g = 4.0$ cm/s, the cross-sectional average gas holdup increases with increasing v_L at all three consistencies. When $v_g = 0.5$ cm/s, this trend is not very strong, with the cross-sectional average gas holdup approximately equal for $v_L = 5.0$ and 7.5 cm/s at $C = 0\%$ and $v_L = 2.5$ and 5.0 cm/s at $C = 0.8\%$.

One interesting trend revealed in Fig. 9 is that the cross-sectional average gas holdup is maximized when $C = 0.8\%$ for $v_g = 4.0$ cm/s and $v_L = 5.0$ or 7.5 cm/s, and for $v_g = 0.5$ cm/s and $v_L = 7.5$ cm/s, although the latter result is not too different from the $C = 0\%$ value. Additionally, for each superficial gas or liquid velocity shown in Fig. 9, the cross-sectional average gas holdup is minimized when $C = 1.2\%$. Therefore, it appears that there is a critical consistency at which gas holdup is maximized, and it depends on superficial gas and liquid velocity.

George [19], using the same cocurrent bubble column apparatus as Lindsay et al. [6, 18], determined that gas holdup in a $C = 1\%$ pulp slurry is higher than that of a simple air/water cocurrent system. Conversely, Lindsay et al. [6, 18] have shown that gas holdup in a $C = 1\%$ pulp slurry in a quiescent bubble column is lower than that of an air/water system. In the quiescent bubble column, cellulose fibers can easily form a network that impedes the movement of small air bubbles. This promotes bubble coalescence and channeling, which leads to larger bubbles breaking through the fiber network and rising to the surface at high speeds. Although cocurrent fiber suspensions also form networks that impede the movement of small bubbles, the liquid movement can carry the small bubbles away before coalescence occurs. The air bubbles remain small and well dispersed, limiting bubble coalescence and channeling, leading to a higher gas holdup compared to an air/water system under similar operating conditions [18].

In the present work, the cross-sectional average gas holdup is maximized at an intermediate pulp consistency (i.e., $C = 0.8\%$) when the superficial liquid velocity is sufficiently high to remove air bubbles from the injector ports at a high enough frequency to diminish bubble coalescence. Additionally, the high superficial liquid velocities promote secondary flows (i.e., backmixing and recirculation) which causes the gas holdup to increase. This is clearly observed when $v_g = 4.0$ cm/s, $v_L = 5.0$ or 7.5 cm/s, and $C = 0.8\%$. When $C = 1.2\%$, the cross-sectional average gas holdup decreases substantially and is attributed to bubble coalescence and channeling. The increased fiber consistency promotes the formation of large bubbles which rise much faster in the column and remain in the column

center and reduce the overall gas holdup [2, 9, 23]. Although there is backmixing observed at this fiber consistency, the large bubbles are unaffected by it. When $v_g = 4.0$ cm/s and $v_l = 2.5$ cm/s, the gas holdup decreases with increasing ONP consistency. At this low superficial liquid velocity, the fibers enhance bubble coalescence and channeling, leading to the gas holdup reduction.

When $v_g = 0.5$ cm/s, the cross-sectional average gas holdup is rather low to begin with ($\sim 2\%$) and the increased backmixing with increasing superficial liquid velocity does not have a considerable effect on the results. There is only a slight increase in gas holdup at $C = 0.8\%$ when $v_l = 7.5$ cm/s. The other superficial liquid velocities result in a reduction in gas holdup with increasing ONP consistency. For these conditions, a maximum gas holdup may occur in the range of $0\% < C < 0.8\%$, but this consistency range was not addressed in this study. The decline in gas holdup with increasing ONP consistency at this low superficial gas velocity is hypothesized to be due to the concentration of the air (gas phase) in the central region of the column [8]. At these low superficial gas velocities, the gas concentration is small and the majority of the gas will migrate toward the column center and may coalesce with other bubbles. The increase in fiber consistency will further promote bubble coalescence, which causes the bubbles to rise faster and reduce the gas holdup. This may also occur at the higher superficial gas velocities, but the churn-turbulent nature of the flow suppresses any influence that may be observed. Although there is backmixing in the channel, the channel core region where the majority of the gas is located, is not significantly affected by it.

Near the top of the column ($H = 132.1$ cm), backmixing is much stronger and the cross-sectional average gas holdup as a function of ONP consistency for this column height is shown in Fig. 10. When $v_g = 4.0$ cm/s and $v_l = 5.0$ or 7.5 cm/s, similar trends to those in Fig. 9 are revealed and gas holdup is maximized at an intermediate pulp consistency ($C = 0.8\%$ in this study). When $v_g = 4.0$ cm/s and $v_l = 2.5$ cm/s, the cross-sectional average gas holdup increases from approximately 10.5% at $C = 0\%$ to approximately 11.2% at $C = 1.2\%$. The small amount of backmixing that occurs at this superficial liquid velocity is confined to the upper region of the column, near $H = 132.1$ cm. This results in the slight increase in gas holdup with increasing ONP consistency for these conditions.

When $v_g = 0.5$ cm/s and $H = 132.1$ cm, the cross-sectional average gas holdup does not differ considerably when the superficial liquid velocity increases from $v_l = 2.5$ cm/s to $v_l = 7.5$ cm/s. As the ONP consistency increases for these conditions, the gas holdup shows a general decrease, and is similar to that observed at $H = 50.8$ cm (Fig. 9). This result is again attributed to the gas phase concentration in the column center [8]. Figures 9 and 10 show that the cross-sectional average gas holdup is influenced by both superficial liquid and gas velocities as well as the fiber consistency and it is a complex relationship.

Figure 11 shows the column-average gas holdup as a function superficial gas velocity for all three ONP fiber consistencies considered in this study and $v_l = 7.5$ cm/s. This figure clearly shows that the column-average gas holdup is maximized at an intermediate pulp consistency ($C = 0.8\%$ in this study) and minimized at a higher pulp consistency ($C = 1.2\%$ in this study) for 0.5 cm/s $\leq v_g \leq 4.0$ cm/s. This trend was not observed by Lindsay et al. [6] or Reese et al. [17] in quiescent bubble columns filled with cellulose fiber suspensions or by Krishna et al. [5] for other slurry suspensions in quiescent bubble columns. Therefore, cocurrent flow conditions are important in maximizing gas holdup in a fiber suspension. The reason why gas holdup is maximized at $C = 0.8\%$ and minimized at $C = 1.2\%$ for the flow conditions of this study is hypothesized to be due to the strength of the fiber network. At $C = 0.8\%$, the fiber network is still "loose" enough to allow for effective air dispersion in the pulp suspension. However, at $C = 1.2\%$, the fiber network is such that air dispersion is obstructed and bubble coalescence is promoted, leading to large bubbles with fast rise velocities and channeling, both of which reduce the overall gas holdup. The presence of large bubbles reducing gas holdup has also been recorded in other bubble column experiments [2, 5, 9, 11, 13, 14].

At $v_g = 0.5$ cm/s, the difference in the column-average gas holdup for the three consistencies is very small. Extrapolating the gas holdup to $v_g = 0$ reveals a column-average gas holdup of approximately 1% for all three consistencies. This may be the result of very small bubbles that are trapped in the pulp suspension and cannot rise to escape [37]. It has been suggested that air bubbles must be larger than approximately 0.3 mm in diameter to rise through a fiber suspension [38]. Figure 11 would suggest that there is a sufficient quantity of very small bubbles entrained in the pulp suspension to produce a column average gas holdup of approximately 1% when the air flowrate is removed ($v_g = 0$). Taylor [20] has also concluded that a 1% consistency pulp suspension can entrain at least 1% (by volume) of air. Lindsay et al. [6] and Douek et al. [23] have also shown similar results when v_g is extrapolated to zero in a cocurrent slurry bubble column.

A second possible explanation for these conclusions when v_g is extrapolated to zero is that the column-average gas holdup may not be linear when $v_g < 0.5$ cm/s. This is suggested by the fact that extrapolating the $C = 0\%$ curve back to $v_g = 0$ produces a column-average gas holdup of approximately 1%. However, no air bubbles were visually observed in the bubble column when $v_g = 0$ for the air/water system. Finally, it may also be possible that there is a systematic error in our gas holdup measurements. However, similar observations from other researchers in other laboratories have also been observed [23].

CONCLUSIONS

Chord-average gas holdup measurements have been obtained at various lateral and vertical locations by gamma-ray densitometry in a cocurrent bubble column, from which cross-sectional average and column-average gas holdup values have been determined. Results were presented for a range of superficial gas velocities ($0.5 \text{ cm/s} \leq v_g \leq 4.0 \text{ cm/s}$), superficial liquid velocities ($2.5 \text{ cm/s} \leq v_l \leq 7.5 \text{ cm/s}$), and ONP fiber consistencies ($0\% \leq C \leq 1.2\%$). Gas holdup has been shown to generally increase with column height, superficial gas velocity, and superficial liquid velocity, for all consistencies addressed in this study. Focusing on the three ONP fiber consistencies addressed in this study (i.e., $C = 0, 0.8$, and 1.2%), column-average gas holdup was maximized when $C = 0.8\%$ and minimized when $C = 1.2\%$. Cross-sectional average gas holdup values typically followed this same trend, but deviations were observed and were influenced by superficial liquid and gas velocity as well as column height.

ACKNOWLEDGMENTS

Portions of this work were used by THS in partial fulfillment of the requirements for the M.S. degree at the Institute of Paper Science and Technology. Financial support of this work by the Institute of Paper Science and Technology and its Member Companies is gratefully acknowledged. The pump upgrade from Diskflo is also appreciated.

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FIGURES

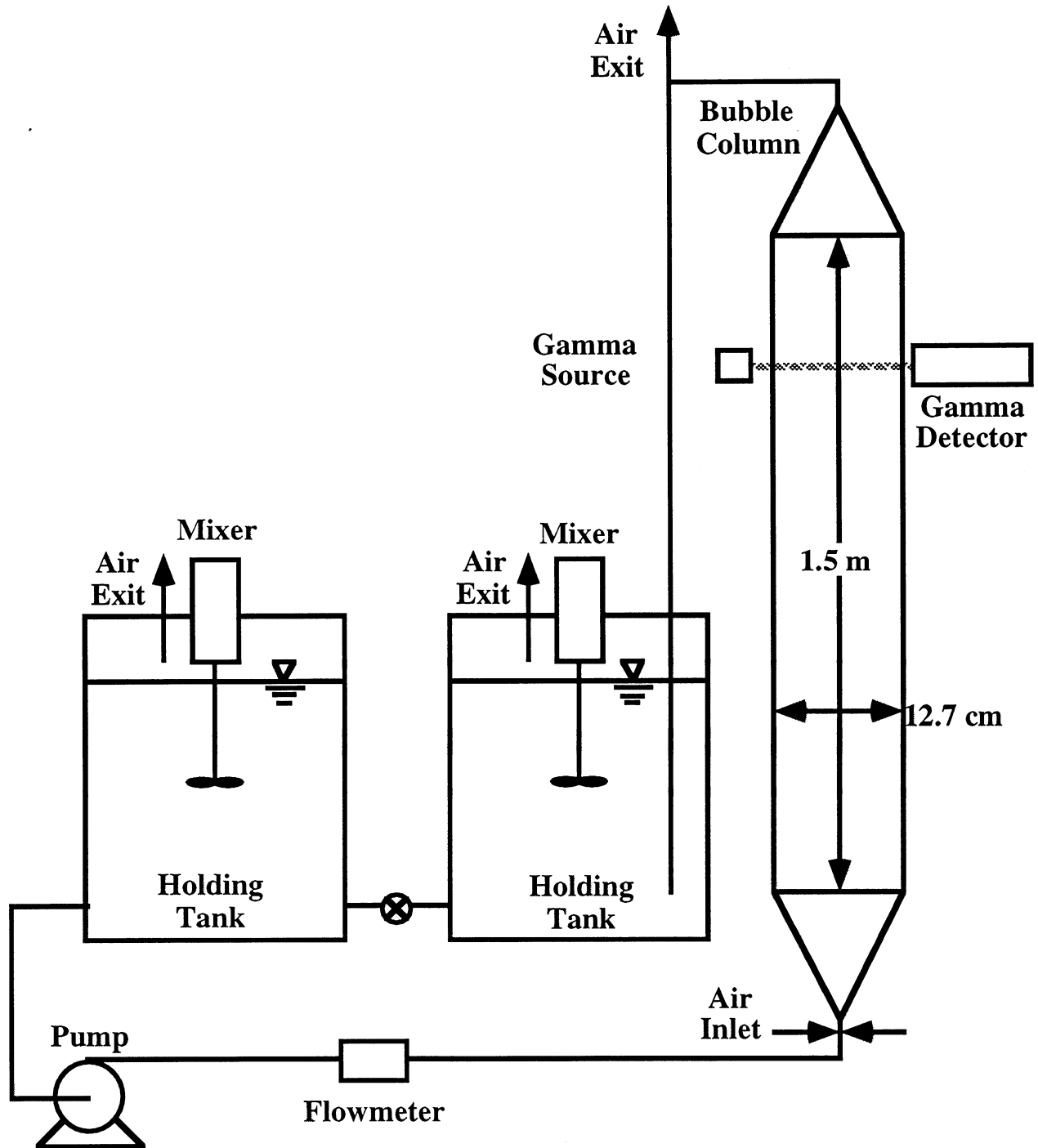


Figure 1: Schematic of the cocurrent bubble column flowloop.

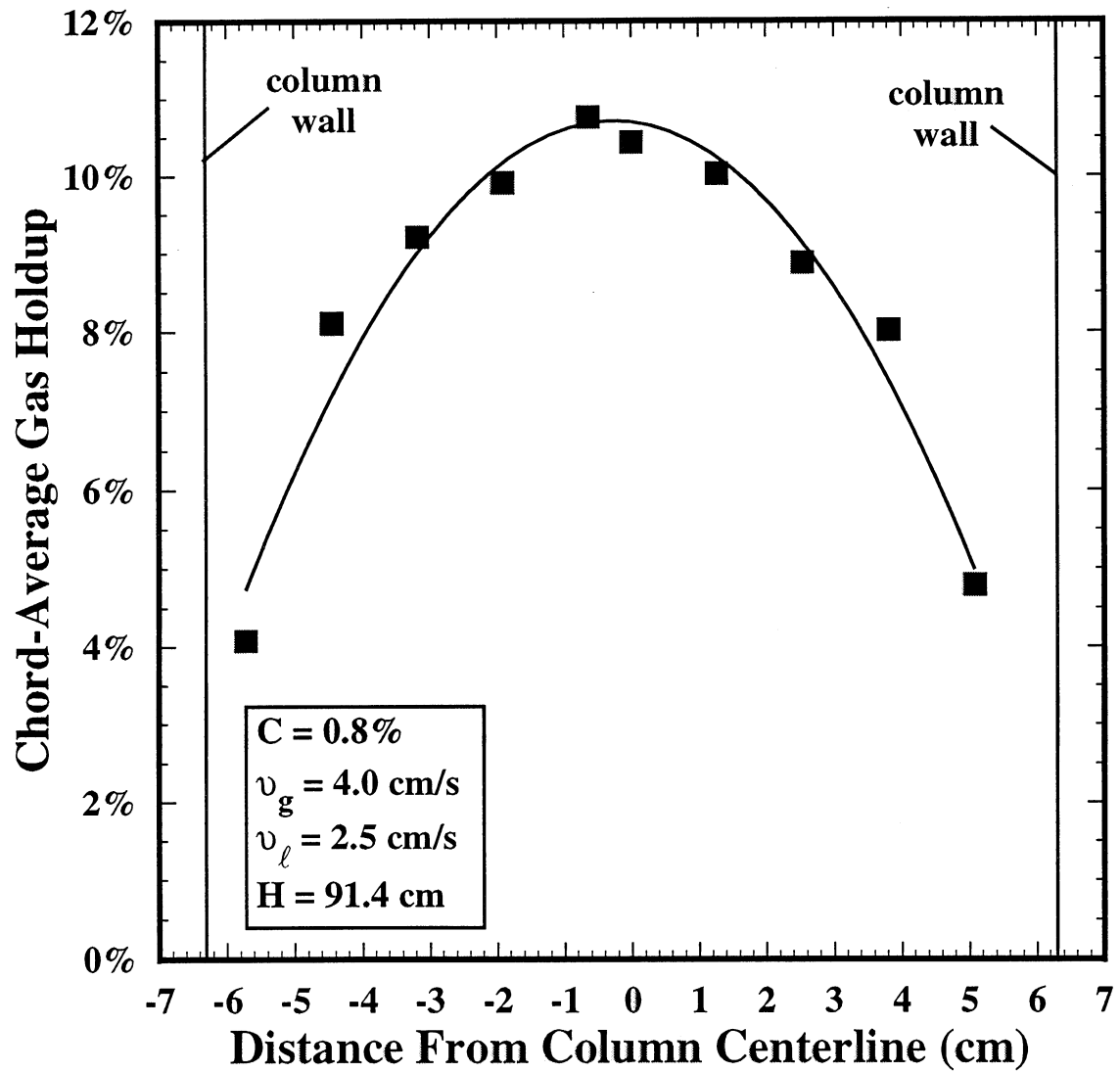


Figure 2: Typical chord-average gas holdup profile.

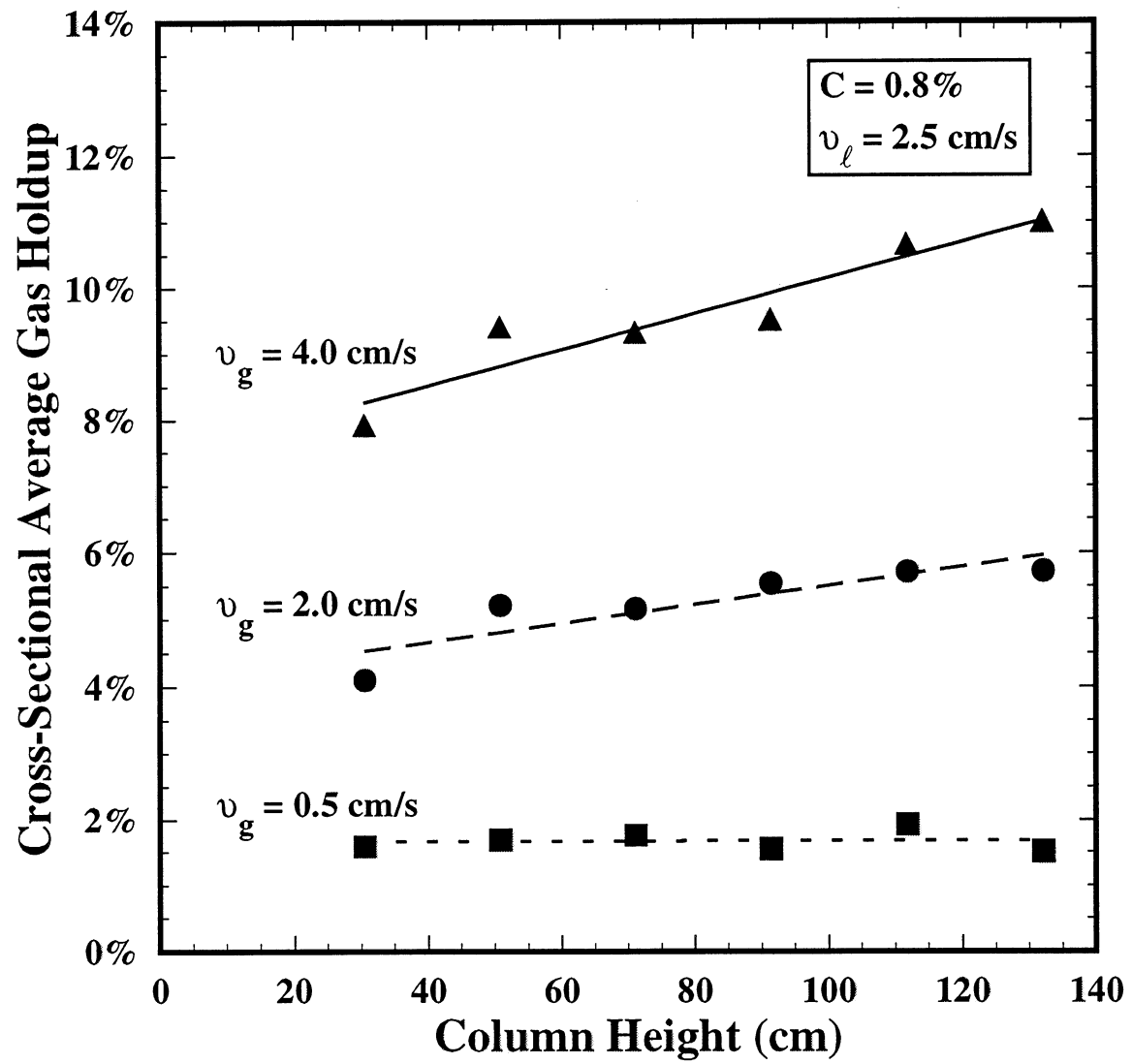


Figure 3: Effect of column height on cross-sectional average gas holdup.

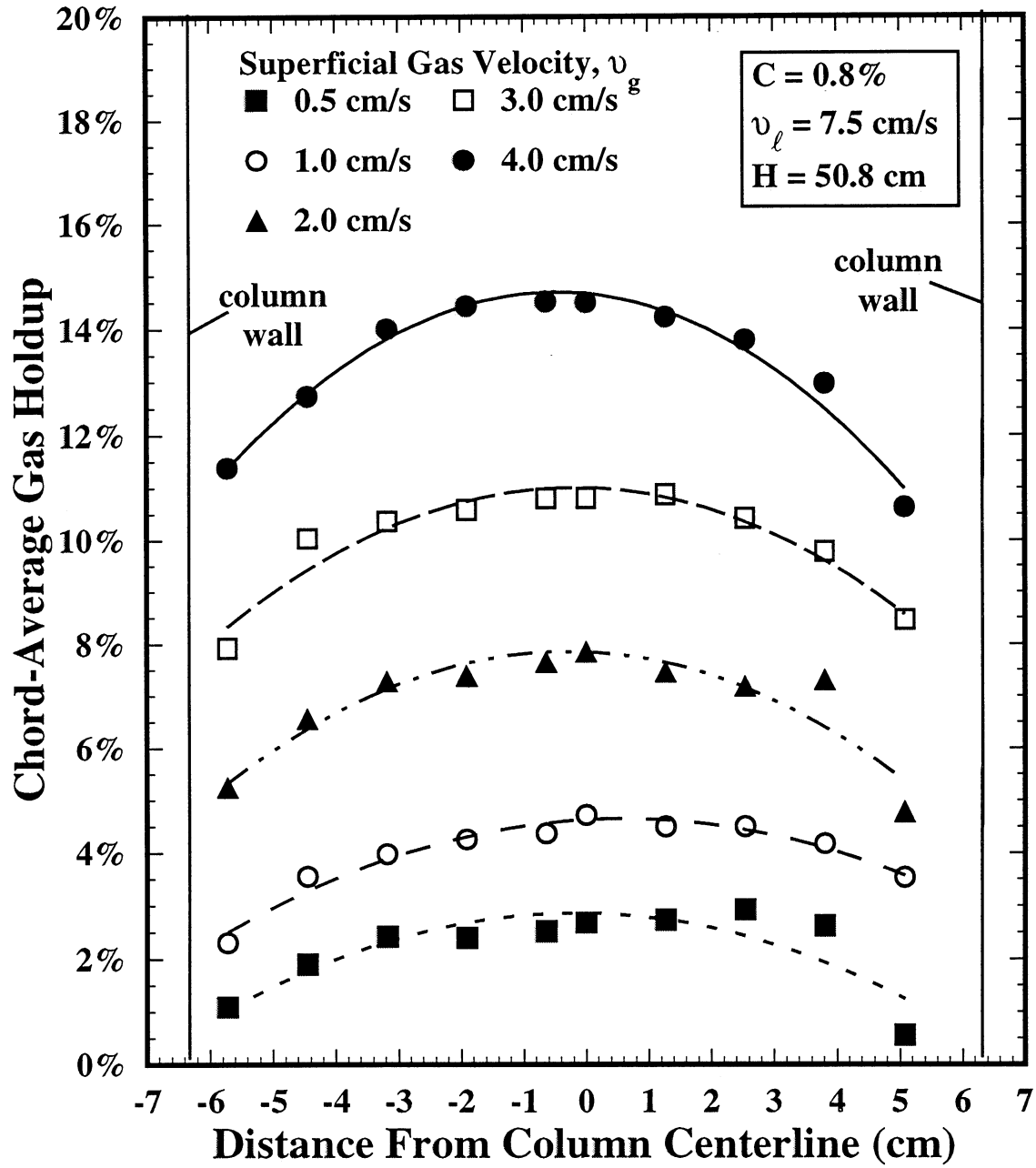


Figure 4: Chord-average gas holdup profiles at various superficial gas velocities for $C = 0.8\%$, $v_\ell = 7.5 \text{ cm/s}$, and $H = 50.8 \text{ cm}$.

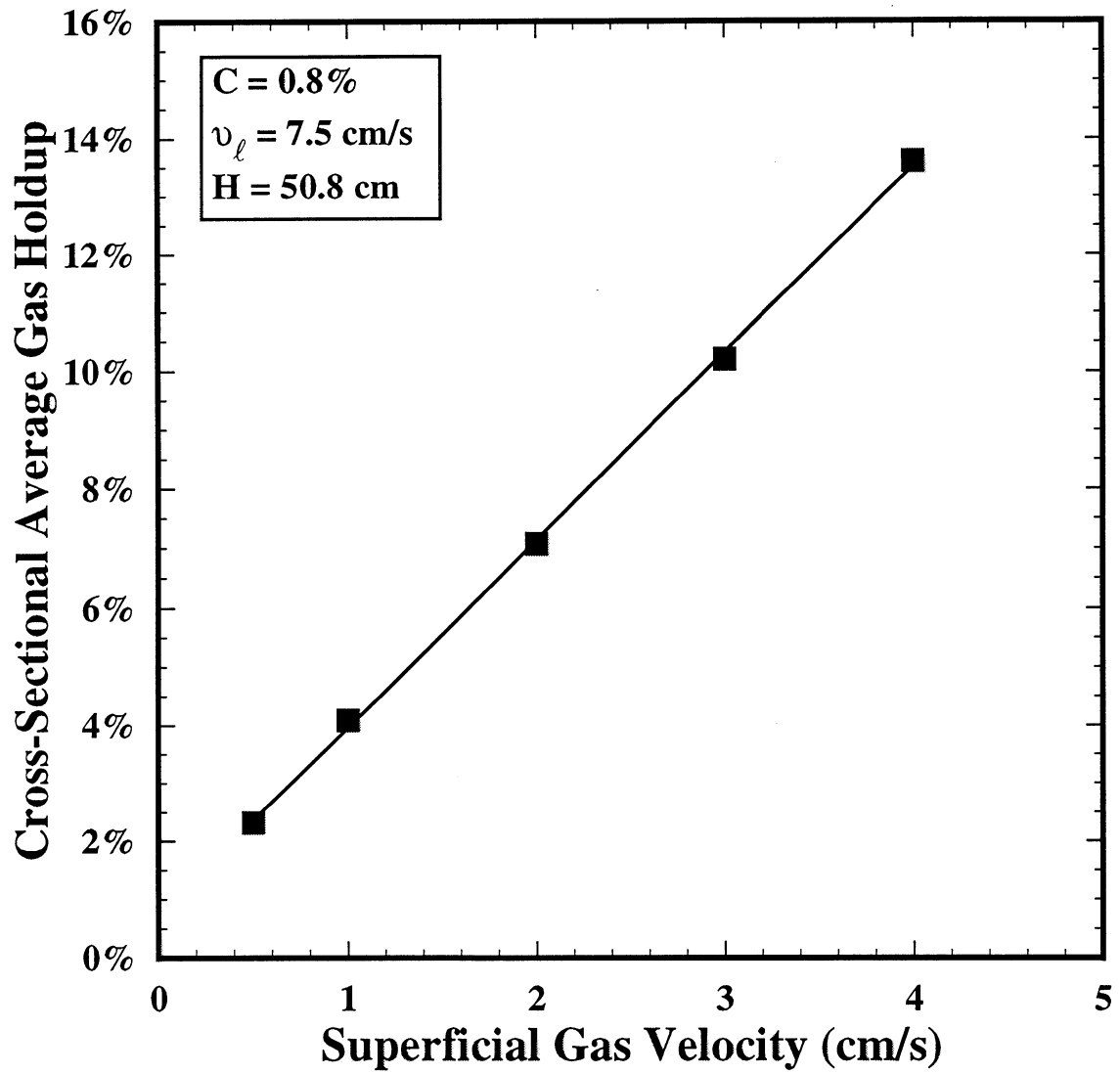


Figure 5: Cross-sectional average gas holdup as a function of superficial gas velocity for $C = 0.8\%$, $v_\ell = 7.5 \text{ cm/s}$, and $H = 50.8 \text{ cm}$.

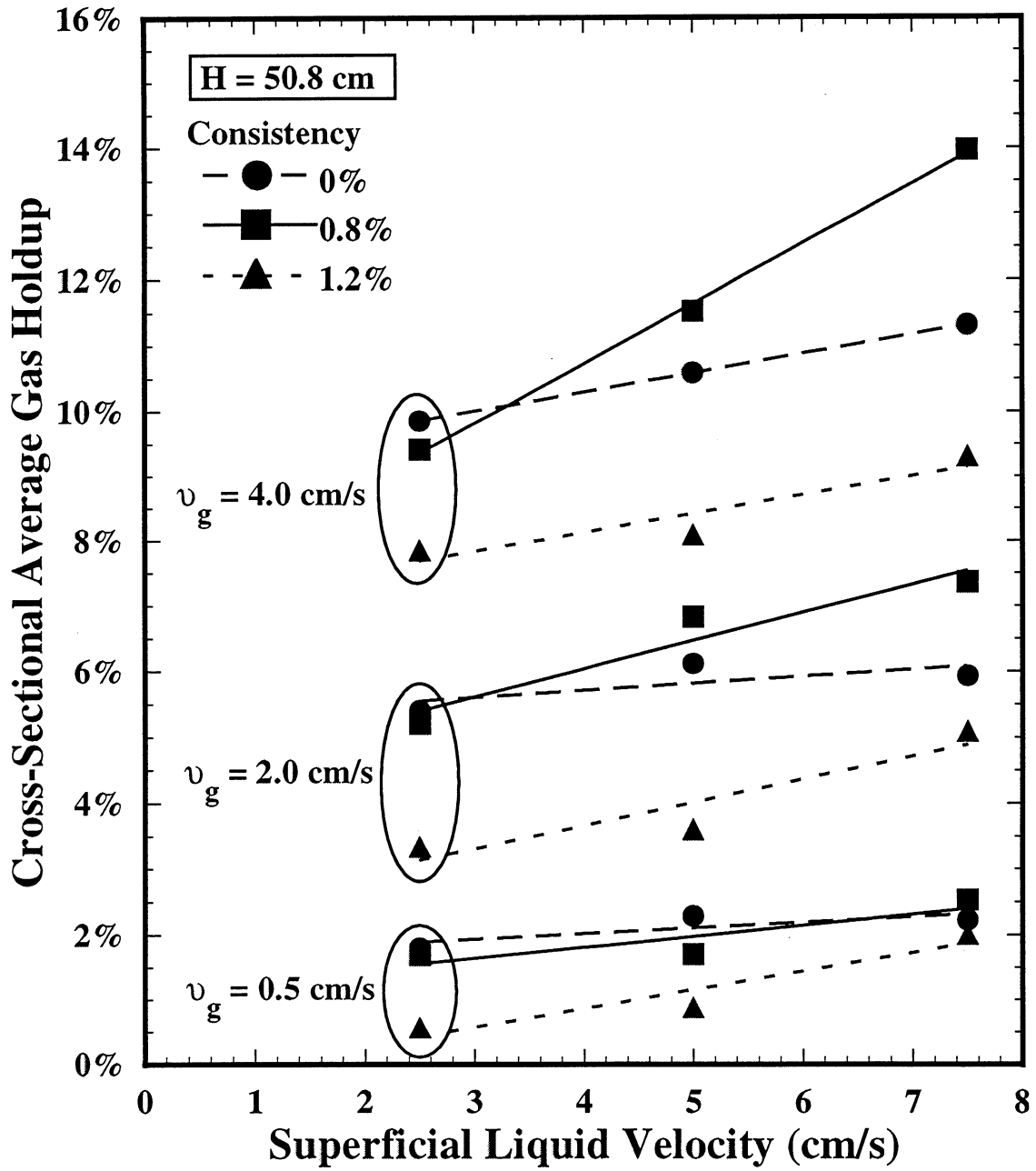


Figure 6: Cross-sectional average gas holdup as a function of superficial liquid velocity at $H = 50.8 \text{ cm}$.

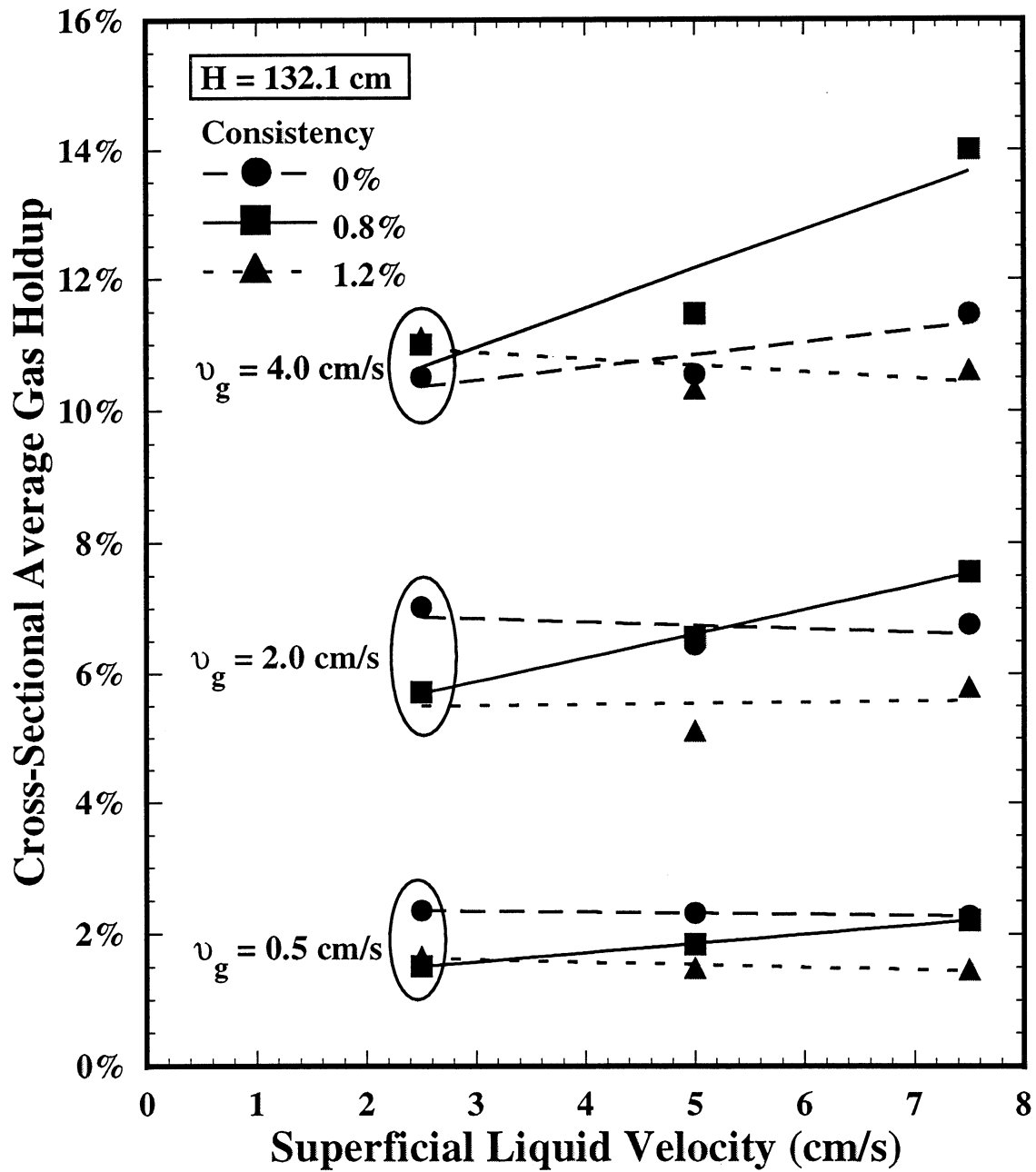


Figure 7: Cross-sectional average gas holdup as a function of superficial liquid velocity at $H = 132.1$ cm.

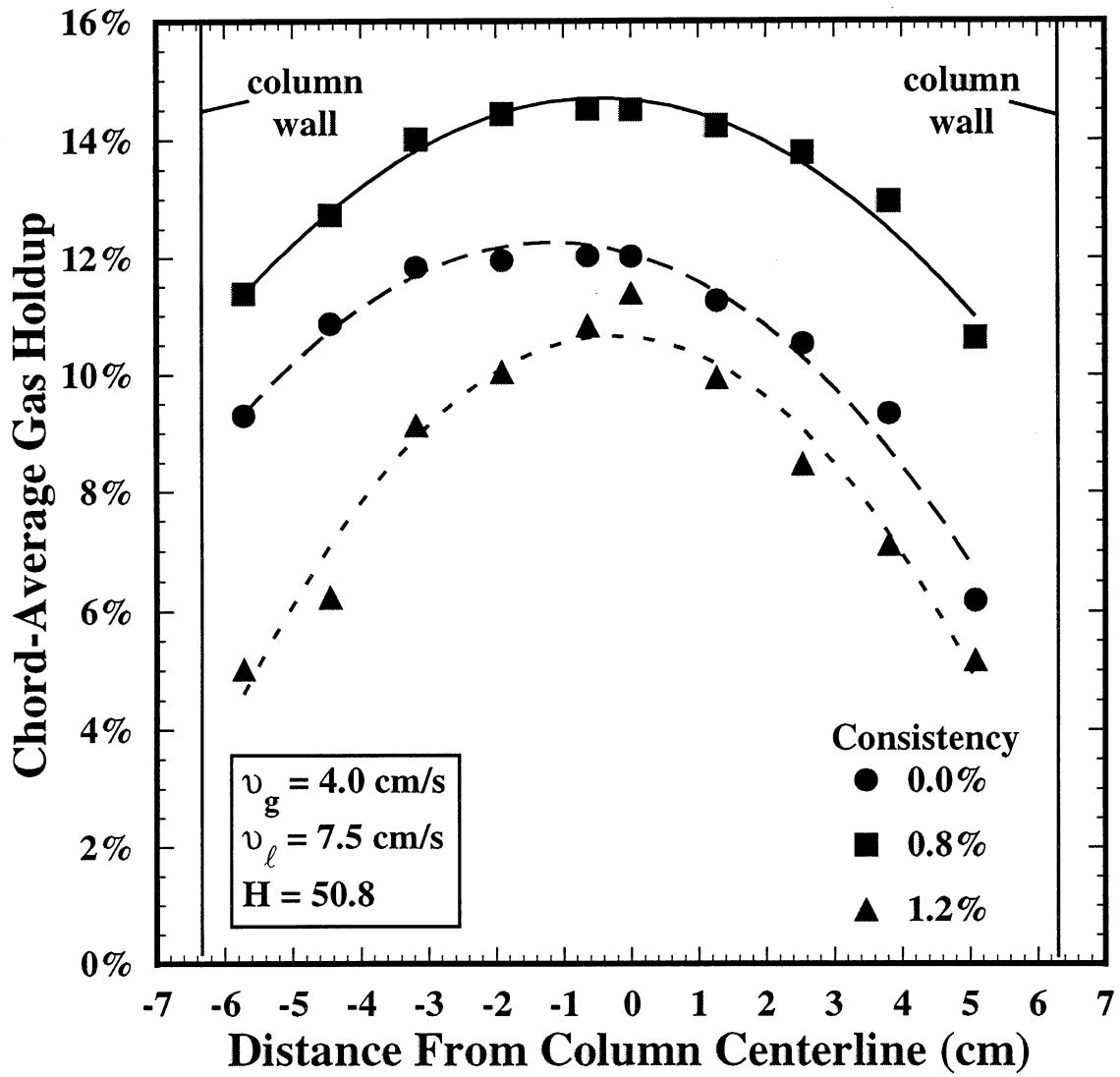


Figure 8: Chord-average gas holdup profiles at three different ONP consistencies for $v_g = 4.0 \text{ cm/s}$, $v_l = 7.5 \text{ cm/s}$, and $H = 50.8 \text{ cm}$.

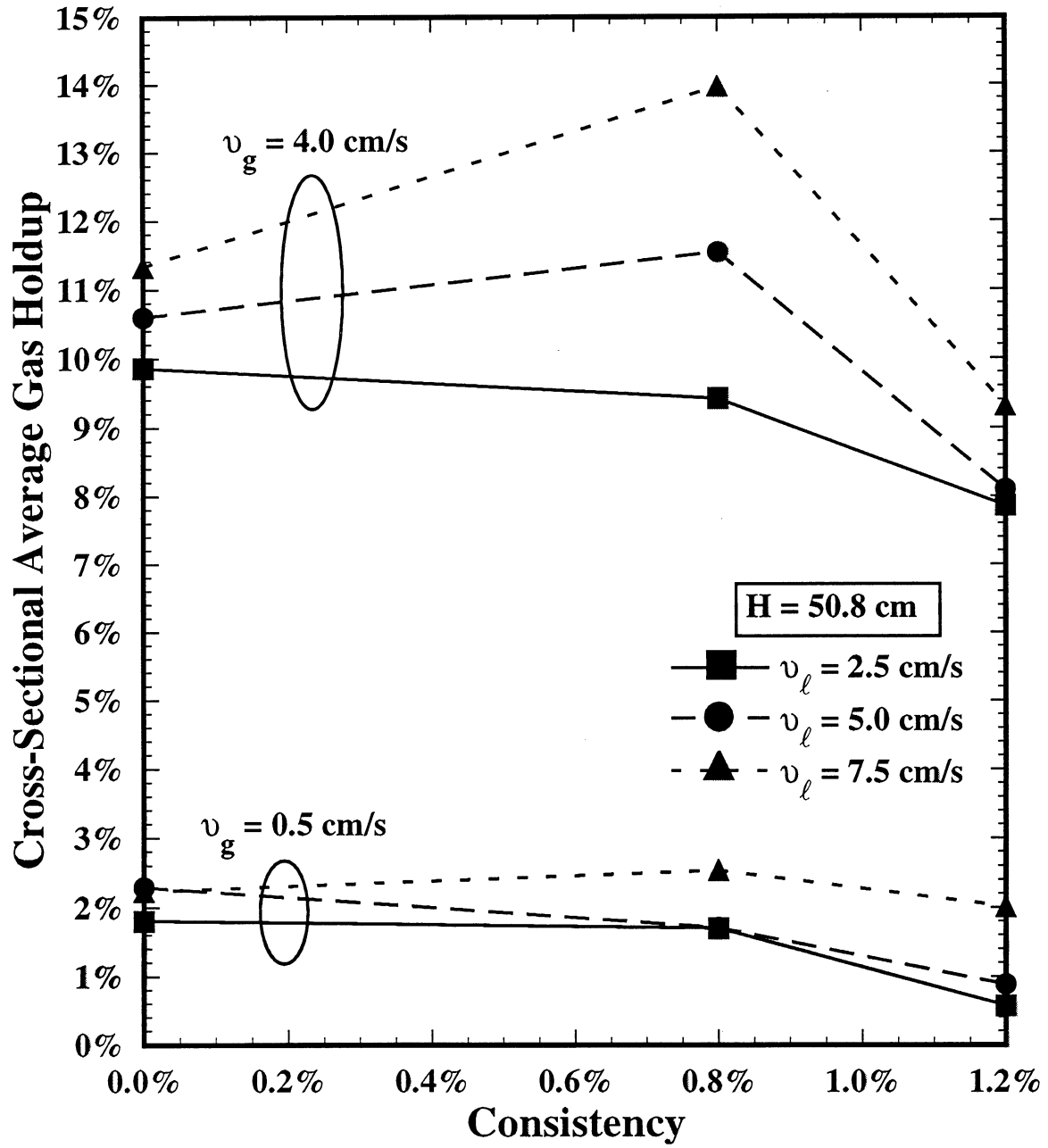


Figure 9: Cross-sectional average gas holdup as a function of ONP consistency at $H = 50.8$ cm.

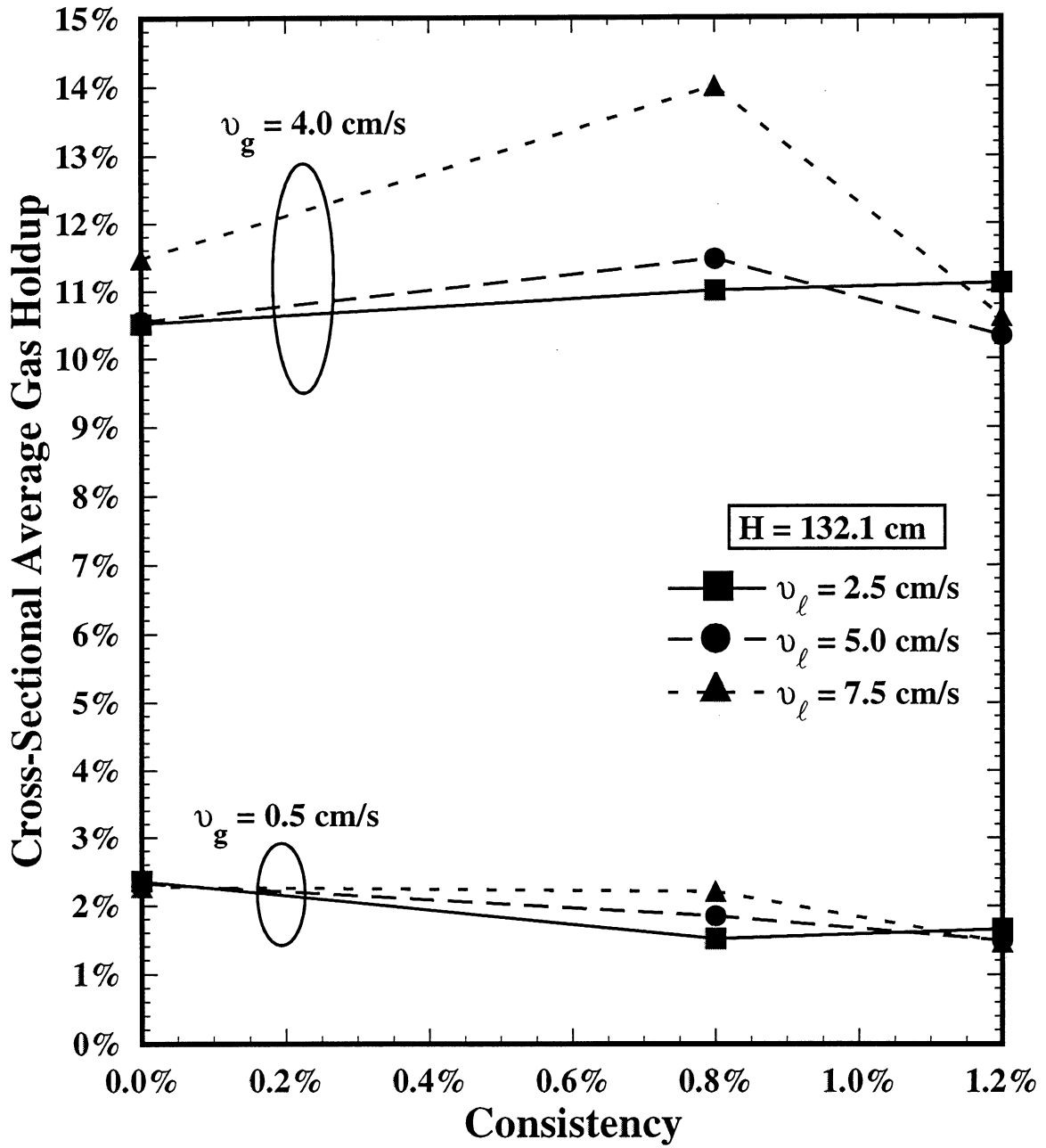


Figure 10: Cross-sectional average gas holdup as a function of ONP consistency at $H = 132.1$ cm.

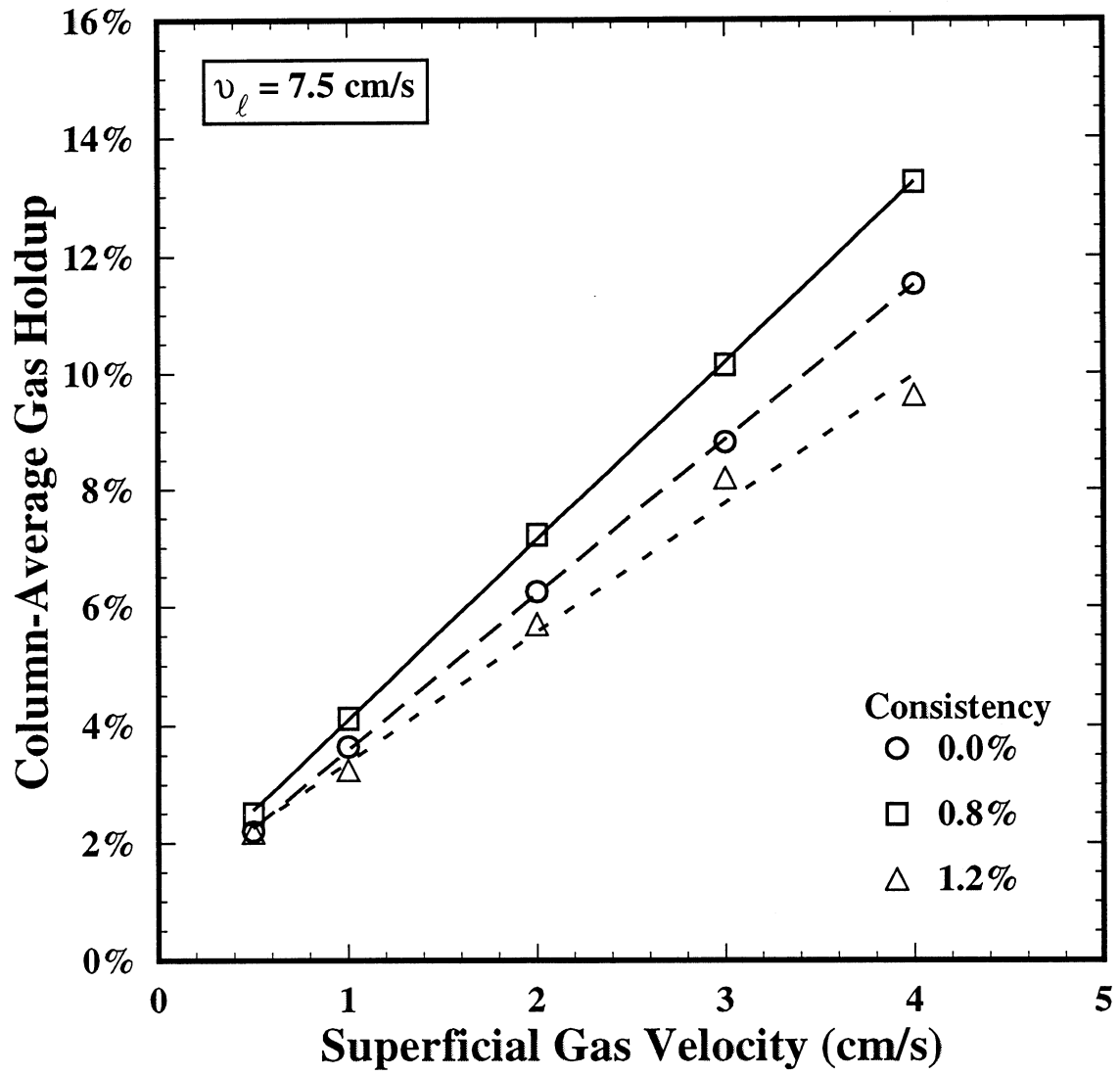


Figure 11: Column-average gas holdup as a function of superficial gas velocity at $v_l = 7.5$ cm/s.

