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Chengzhi Tang  
*Iowa State University*

Theodore J. Heindel  
*Iowa State University, theindel@iastate.edu*

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# Gas Holdup in a Cocurrent Air-Water-Fiber Bubble Column

## Abstract

Effects of superficial liquid velocity ( $Ul$ ), superficial gas velocity ( $Ug$ ), and fiber mass fraction ( $C$ ) on gas holdup ( $\epsilon$ ) and flow regime transition are studied experimentally in well-mixed water-cellulose fiber suspensions in a cocurrent bubble column. Experimental results show that the gas holdup decreases with increasing  $Ul$  when  $C$  and  $Ug$  are constant. The gas holdup is not significantly affected by  $C$  in the range of  $C < 0.4\%$ , but decreases with increasing  $C$  in the range of  $0.4\% \leq C \leq 1.5\%$ . When  $C > 1.5\%$ , a significant amount of gas is trapped in the fiber network and recirculates with the water-fiber slurry in the system; as a result, the measured gas holdup is higher than that at  $C = 1.5\%$ . The axial gas holdup distribution is shown to be a complex function of superficial gas and liquid velocities and fiber mass fraction. The drift-flux model is used to analyze the flow regime transitions at different conditions. Three distinct flow regimes are observed when  $C \leq 0.4\%$ , but only two are identified when  $0.6\% \leq C \leq 1.5\%$ . The superficial gas velocities at which flow transition occurs from one regime to another are not significantly affected by  $Ul$  and slightly decrease with increasing  $C$ .

## Keywords

bubble column, cellulose fiber, gas holdup, hydrodynamics, multiphase flow

## Disciplines

Acoustics, Dynamics, and Controls | Complex Fluids | Fluid Dynamics | Polymer and Organic Materials

## Comments

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## GAS HOLDUP IN A COCURRENT AIR-WATER-FIBER BUBBLE COLUMN

Chengzhi Tang

Iowa State University

Department of Mechanical Engineering

Ames, Iowa 50011-2161

Phone: 515-294-0913, Fax: 515-294-3261

Email: cztang@iastate.edu

Theodore J. Heindel\*

Iowa State University

Department of Mechanical Engineering

Ames, Iowa 50011-2161

Phone: 515-294-0057, Fax: 515-294-3261

Email: theindel@iastate.edu

### ABSTRACT

Effects of superficial liquid velocity ( $U_l$ ), superficial gas velocity ( $U_g$ ), and fiber mass fraction ( $C$ ) on gas holdup ( $\varepsilon$ ) and flow regime transition are studied experimentally in well-mixed water-cellulose fiber suspensions in a cocurrent bubble column. Experimental results show that the gas holdup decreases with increasing  $U_l$  when  $C$  and  $U_g$  are constant. The gas holdup is not significantly affected by  $C$  in the range of  $C < 0.4\%$ , but decreases with increasing  $C$  in the range of  $0.4\% \leq C \leq 1.5\%$ . When  $C > 1.5\%$ , a significant amount of gas is trapped in the fiber network and recirculates with the water-fiber slurry in the system; as a result, the measured gas holdup is higher than that at  $C = 1.5\%$ . The axial gas holdup distribution is shown to be a complex function of superficial gas and liquid velocities and fiber mass fraction. The drift-flux model is used to analyze the flow regime transitions at different conditions. Three distinct flow regimes are observed when  $C \leq 0.4\%$ , but only two are identified when  $0.6\% \leq C \leq 1.5\%$ . The superficial gas velocities at which flow transition occurs from one regime to another are not significantly affected by  $U_l$  and slightly decrease with increasing  $C$ .

KEYWORDS: Bubble column; Cellulose fiber; Gas holdup; Hydrodynamics; Multiphase flow

### NOMENCLATURE

$B_0$  coefficient in Eq. (3),  $B_0 = C_0 U_l + U_{b\infty}$

$C$  fiber mass fraction

$C_0$  coefficient in Eq. (2) and Eq. (3)

$H$  axial position along bubble column, m  
 $p$  pressure, Pa  
 $U$  superficial velocity, cm/s  
 $U_{b\infty}$  terminal rise velocity of a single bubble in an infinite medium, cm/s

### Greek letters

$\varepsilon$  gas holdup, or average gas holdup in the lower 3 sections  
 $\Delta$  difference

### Subscripts

$g$  gas phase  
 $H$  higher end  
 $i$  section number,  $i = 1, 2, 3$ , or 4  
 $L$  lower end  
 $l$  liquid phase

### INTRODUCTION

Gas-liquid-cellulose fiber systems are found in the pulp and paper industry in a variety of unit operations including flotation deinking, direct-contact steam heating, gaseous fiber bleaching and papermaking [1]. In processes such as flotation deinking, direct-contact steam heating, and bleaching, gases are intentionally introduced into the system and it is important to create a homogeneous mixture with sufficient interfacial area

\*Corresponding author

for mass and/or heat transfer. In contrast, deaeration is used to remove unwanted gas from the system.

Water-cellulose fiber systems are unique because the cellulose fibers have a density close to that of water. A water-fiber suspension is also considered a pseudoplastic fluid [2,3], which acts as a non-Newtonian fluid above a shear stress threshold and acts as a solid otherwise. The shear stress threshold has been shown to increase with fiber mass fraction [2,3]. Fiber suspensions also have a tendency to form regions where the fibers aggregate (i.e., flocculate) at mass fraction as low as  $C = 0.3\%$  and continuous fiber networks when  $C \geq 1\%$  [4]. Factors affecting floc formation and deformation include flow conditions, fiber length, and fiber stiffness [3].

In previous studies of gas-liquid-cellulose fiber cocurrent bubble columns, gas holdup was found to increase with increasing superficial gas velocity [5-7]. The effect of superficial liquid velocity on gas holdup was found to be rather complex. Lindsay et al. [5] reported superficial liquid velocity had a negligible effect on gas holdup in an air-water two-phase cocurrent bubble column with a 12.7 cm diameter. Using the same column, Schulz and Heindel [6] concluded that the cross-sectional averaged gas holdup at a low column position increased with superficial liquid velocity ( $2.5 \leq U_l \leq 7.5$  cm/s) at all studied fiber mass fractions while this was observed only at an intermediate fiber mass fraction at a higher column position. However, using a 5.1 cm diameter cocurrent bubble column, Xie et al. [7] reported gas holdup decreased with increasing superficial liquid velocity when  $21 \leq U_l \leq 51$  cm/s.

The effect of fiber mass fraction on gas holdup in a cocurrent gas-liquid-cellulose fiber system has also been shown to be complicated. Lindsay et al. [5] reported that when their system contained  $C = 1\%$  fiber, gas holdup was higher than that of the column filled with water under the same flow conditions. Studying  $C = 0, 0.8\%$ , and  $1.2\%$  fiber systems, Schulz and Heindel [6] showed that the column-average gas holdup was highest at  $C = 0.8\%$  and lowest at  $C = 1.2\%$  when all other conditions were constant. This was also observed by Xie et al. [7] in their smaller diameter column. It is reasonable to consider that the highest gas holdup obtained at the intermediate fiber mass fraction was due to some complex interactions between superficial liquid velocity and fiber mass fraction, since gas holdup has been shown to decrease with increasing fiber mass fraction in semi-batch bubble columns due to enhanced bubble coalescence [5, 8-10].

Several investigators have studied gas flow regime changes in gas-liquid-cellulose fiber bubble columns. Walmsley [11] observed bubbly flow and churn-turbulent flow in a 2-D semi-batch column and two 3-D semi-batch columns of different aspect ratios. Lindsay et al. [5] recorded bubbly flow and churn-turbulent flow in a 12.7 cm semi-batch bubble column and a 12.7 cm cocurrent bubble column with  $C = 1\%$  or  $2\%$ . Reese et al. [9] found that in a 10.2 diameter cylindrical semi-batch bubble column filled with a fiber suspension, dispersed bubble, vortical-spiral, and turbulent flow could be identified when the fiber mass fraction was low ( $C \leq 0.5\%$ ),

while only dispersed bubble and turbulent flow were recorded at high fiber mass fractions ( $C > 0.5\%$ ). In a 1 m tall 2-D semi-batch bubble column with a rectangular cross-section of 20 cm  $\times$  2 cm, Heindel [12] observed vortical, churn-turbulent, surge churn-turbulent and discrete channel flow as the fiber mass fraction increased from 0% to 5% with a fixed superficial gas velocity of 0.83 cm/s. In a 1.80 m tall 5.1 cm diameter cocurrent bubble column, Xie et al. [7] identified five distinct flow regimes in an air-water-cellulose fiber suspension, including dispersed bubbly, layered bubbly, (incipient plug and) plug, churn-turbulent, and slug flows. The superficial gas velocity at which flow regime transition occurs has also been shown to decrease with fiber addition [5, 7, 11, 13].

In both semi-batch [5] and cocurrent bubble columns [5, 6], the cross-sectional average gas holdup was reported to increase with increasing vertical distance from the column bottom and was attributed to fiber suspension recirculation near the column top. Schulz and Heindel [6] observed that the increase in cross-sectional average gas holdup with position was enhanced with increasing superficial gas velocity when  $U_g > 2.0$  cm/s.

In this paper, a detailed experimental study of superficial liquid velocity, superficial gas velocity, and fiber mass fraction on gas holdup, axial gas holdup variation, and flow regime transition in well-mixed air-water-cellulose fiber suspensions are reported for  $U_l \leq 10$  cm/s,  $U_g \leq 22$  cm/s, and  $C \leq 2\%$ .

## EXPERIMENTAL PROCEDURES

The experiments for this study are conducted in a cylindrical cocurrent bubble column, which consists of four 0.914 m tall acrylic tubes with 15.24 cm internal diameter. Five delrin collars, each 5.1 cm tall, and 11 buna-n gaskets are used to connect the acrylic tubes for a total column height of 4 m. Figure 1 shows a schematic of the entire system. Filtered air is supplied by a compressor and enters the bubble column from the bottom via a spider sparger. The air flowrate is adjusted with a regulator and measured with one of three gas flowmeters, each covering a different flowrate range. The fiber suspension from a 379 L reservoir is pumped into the column. The pump is connected to the reservoir with a 2.44 m long 7.62 cm diameter PVC pipe. A 2.85 m long 2.54 cm diameter PVC pipe connects the pump to the column. The fiber suspension flowrate is measured with a magnetic flowmeter and varied via a pump power frequency controller. The fiber suspension enters the column through a flow expander and flow straightener to provide a nearly uniform liquid velocity field at the entrance region prior to the spider sparger. A gas-liquid separator is located on top of the column where air is separated from the water while the water returns to the reservoir through a PVC pipe. Along the column, 5 pressure transducers ( $P_1, P_2, P_3, P_4,$  and  $P_5$ ) are installed, one in each of the five delrin collars. Each acrylic tube section is numbered 1 to 4 from the bottom of the column. Two type-T thermocouples are also located at the bottom and top of the column, respectively. All pressure,

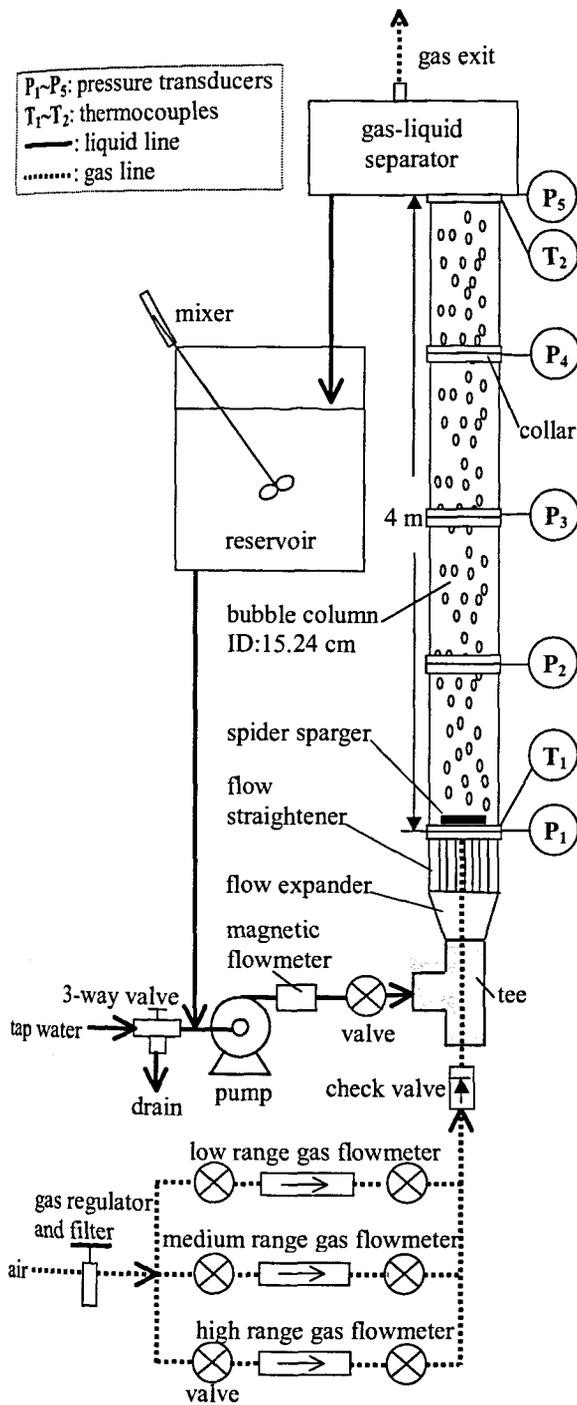


Figure 1. Schematic of the cocurrent bubble column experimental facility.

flowmeter, and thermocouple signals are collected via a computer controlled data acquisition system. Superficial gas and liquid velocities are controlled by the gas regulator and pump power frequency controller, respectively.

The spider sparger, shown in Fig. 2, has eight arms made of 12.7 mm diameter stainless steel tubes. Thirty-three 1.6 mm diameter holes are located on one side of each arm and distributed as shown in Fig. 2. The arms are soldered to the

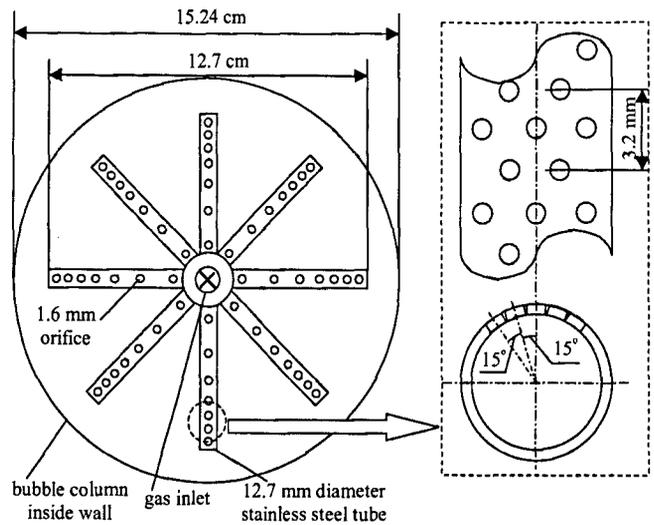


Figure 2. Schematic of the spider sparger.

center cylinder of the sparger such that all the holes face the same direction. Air enters the spider sparger from the central cylinder and exits from the arm holes. The sparger is installed with the holes facing upward. Each time an experiment is initiated, attention is paid to prevent water from entering the sparger so that the bubble generation process is not influenced by water inside the sparger body. This is implemented by turning on the gas flow before water rises to the sparger.

All experiments in this study are carried out under atmospheric pressure and ambient temperature. The superficial gas velocity range is  $0 \text{ cm/s} \leq U_g \leq 22 \text{ cm/s}$ , and the superficial liquid velocity range is  $0 \text{ cm/s} \leq U_l \leq 10 \text{ cm/s}$ . Eucalyptus wood fiber and tap water comprise the fiber suspension. The fibers have a length-weighted average fiber length of  $\sim 0.8 \text{ mm}$  and a fiber coarseness index of  $\sim 7.2 \text{ mg/100m}$ . All the fibers are disintegrated from dry lap fiber sheets. The fiber sheets are originally torn into small pieces and then a specified mass of oven-dry fiber is weighed. It is then soaked in tap water for 24 hours before the pieces of fiber sheet are disintegrated in a Black-Clawson laboratory hydropulper. The concentrated fiber suspension is then transferred to the reservoir and additional tap water is added to raise the suspension to a predetermined level. Fiber mass fraction  $C$  is defined as the ratio of the oven-dry fiber mass to the suspension mass. Since the mass fraction in this study is relatively low ( $0 \leq C \leq 2\%$ ), the mass of fiber is neglected in the total suspension mass.

To acquire gas holdup data at a given  $U_g$  and  $U_l$ , 4800 readings are collected from each instrument every 10 ms and averaged after quasi-steady conditions are reached. With five pressure signals, the time-averaged gas holdup in each section is calculated from

$$\varepsilon_i = 1 - \frac{\Delta p_i}{\Delta p_{0,i}} \quad (1)$$

where  $\Delta p_i = p_{L,i} - p_{H,i}$  is the pressure difference between the lower ( $p_{L,i}$ ) and higher ( $p_{H,i}$ ) ends of column section  $i$  ( $i = 1, 2, 3, 4$ );  $\Delta p_{0,i}$  is the corresponding pressure difference when the column is filled only with the specified water-fiber suspension flowing at the same  $U_l$ . Equation (1) accounts for the effects of wall shear stress but neglects the effect of liquid acceleration due to void changes that may influence gas holdup in cocurrent bubble columns [14-16]; however, these effects were estimated to be negligible for the conditions of this study. The overall column gas holdup is defined as  $\varepsilon = (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/3$ , the average gas holdup in the three lower sections. The gas holdup in the top section is not included in the overall gas holdup because the measurement error due to the void caused by large bubbles escaping the column top is significant during some experimental conditions (see details in the following results).

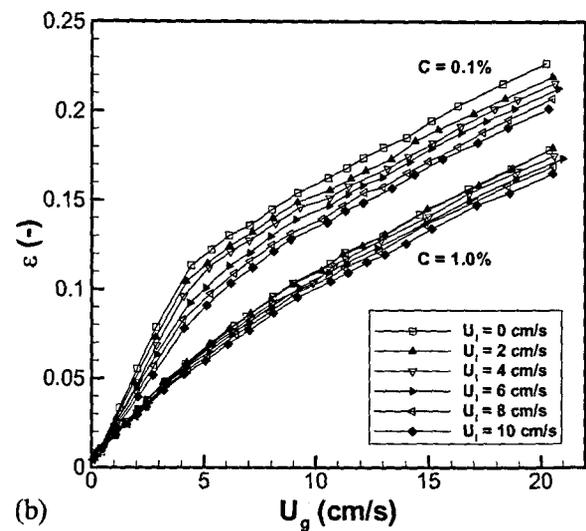
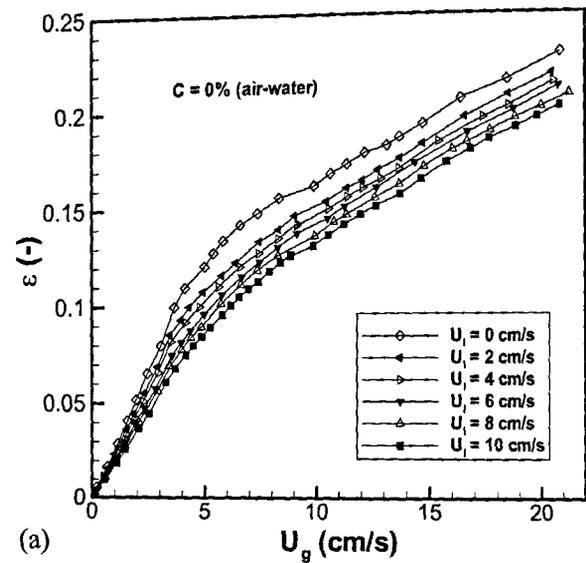
## RESULTS

### Effect of Superficial Gas Velocity

Figure 3 shows the variation of  $\varepsilon$  with  $U_g$  at different  $U_l$  and  $C$  in a cocurrent bubble column. Gas holdup increases with increasing  $U_g$  for all conditions addressed in this study. There is no local gas holdup maximum, which is observed at low fiber mass fractions in a 15.24 cm air-water-Rayon fiber semi-batch bubble column with a perforated plate gas distributor [10]. At low fiber mass fractions ( $C = 0.1\%$ , Fig. 3b), the gas holdup is similar to that of an air-water system ( $C = 0\%$ , Fig. 3a). When  $U_g \leq 4$  cm/s, gas holdup increases proportionally with  $U_g$ . At  $U_g \approx 0$  cm/s, gas holdup is very close to zero, suggesting no air entrainment in the fiber suspension. When  $U_g \geq 13$  cm/s, gas holdup linearly increases with  $U_g$ , but the slope is less than that when  $U_g \leq 4$  cm/s. At high fiber mass fractions ( $C = 1.0\%$ ), gas holdup also increases with  $U_g$ . At  $U_g \approx 0$  cm/s, gas holdup is nonzero, due to a small amount of air entrained in the fiber suspension. The small amount of entrained air can actually be observed in the pump suction line. Similar results were reported by Lindsay et al. [5] and were attributed to the same reason.

### Effect of Superficial Liquid Velocity

Generally, gas holdup decreases linearly with increasing  $U_l$  providing  $U_g$  and  $C$  are constant. Figure 3 shows the results for  $C = 0\%$ ,  $0.1\%$  and  $1.0\%$ . The effect of  $U_l$  on  $\varepsilon$  is similar when  $C = 0.1\%$  and  $0\%$ . When  $C = 1.0\%$  (Fig. 3b), gas holdup still decreases with increasing  $U_l$ , albeit over a smaller  $\varepsilon$  range. Figure 4 compares the trend of  $\varepsilon$  with increasing  $U_l$  at different  $C$  when  $U_g = 13$  cm/s. As shown, the effect of  $U_l$  on  $\varepsilon$  is more evident at lower  $C$ . The decrease in gas holdup with increasing superficial liquid velocity was also reported by Xie et al. [7] in a 5.1 cm cocurrent bubble column. However, Schulz and Heindel [6] observed that the cross-sectional averaged gas holdup increased with  $U_l$  when  $C = 0\%$ ,  $0.8\%$  or  $1.2\%$  at a



**Figure 3.** Variation of gas holdup with superficial gas velocity at different superficial liquid velocities; (a)  $C = 0\%$ , (b)  $C = 0.1\%$  and  $1\%$ .

lower position ( $H = 50.8$  cm) but this trend was significant only when  $C = 0.8\%$  at a higher position ( $H = 132.1$  cm). The difference between the experimental results may be attributed to the different gas distribution methods, different fibers types, and different bubble column geometries, including the exit conditions, used in those studies. More research is necessary to fully understand the influence of superficial liquid velocity on gas holdup in fiber suspensions.

### Effect of Fiber Mass Fraction

Figure 5 shows the effect of fiber mass fraction on gas holdup when  $U_l = 8$  cm/s and  $0 \text{ cm/s} \leq U_g \leq 22$  cm/s. When  $C < 0.4\%$ , the  $\varepsilon$ - $U_g$  curves overlap, indicating a negligible influence of fiber mass fraction on gas holdup. When  $U_g \geq 2$  cm/s, starting with  $C = 0.4\%$ ,  $\varepsilon$  decreases significantly with  $C$  when  $C \leq 1.5\%$  and  $U_g$  and  $U_l$  are constant. When  $U_g \approx 0$ ,  $\varepsilon$

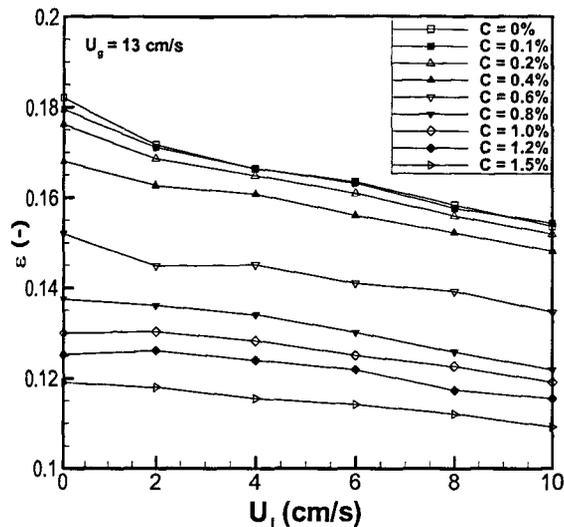


Figure 4. Variation of gas holdup with superficial liquid velocity at different fiber mass fractions ( $U_g = 13$  cm/s).

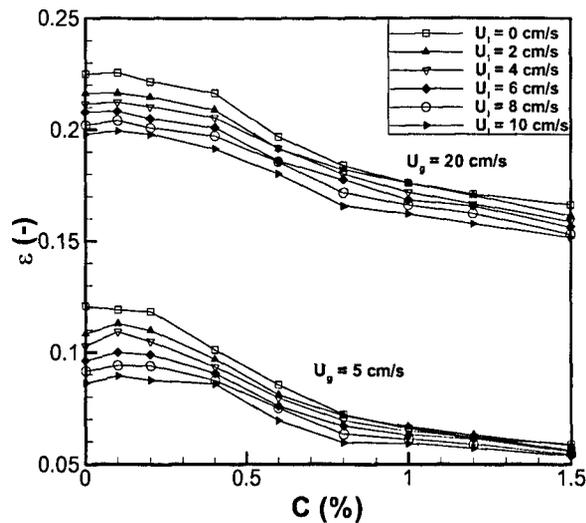


Figure 6. Variation of gas holdup with fiber mass fraction at different superficial liquid velocities.

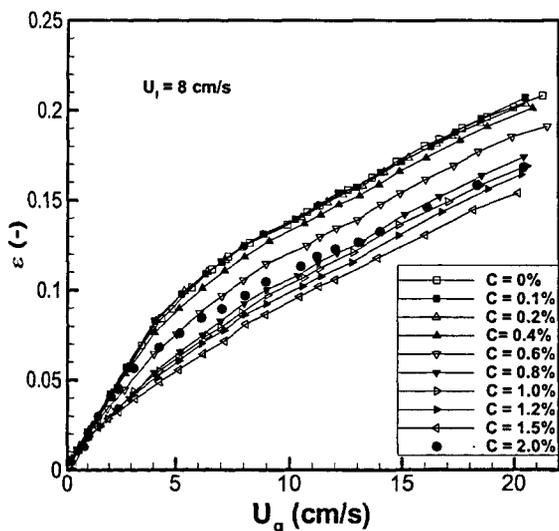


Figure 5. Variation of gas holdup with superficial gas velocity in suspensions of different fiber mass fractions ( $U_l = 8$  cm/s).

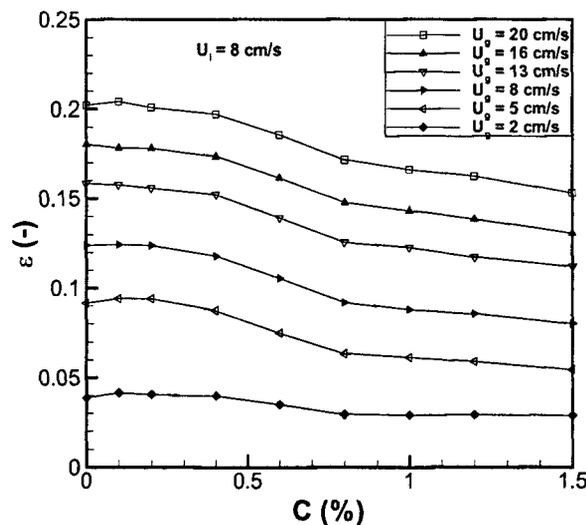


Figure 7. Variation of gas holdup with fiber mass fraction at different superficial gas velocities ( $U_l = 8$  cm/s).

at higher  $C$  are a little higher than those at lower  $C$  because of gas entrainment ( $\sim 0.5\%$ ) in the fiber suspension. When  $C$  is increased to 2.0%, the gas holdup is higher than that at  $C = 1.0\%$ , 1.2% and 1.5% over the entire range of superficial gas velocities. This is attributed to a significant increase in the amount of gas trapped inside the fiber suspension, which is not released in the gas-liquid separator or the reservoir when  $C = 2.0\%$ . The increase in the amount of retained gas in the fiber network is larger than the decrease in gas holdup associated with an increase in fiber mass fraction. This agrees with Lindsay et al. [5], who found the amount of gas retained in the fiber suspension increased with  $U_g$  much faster when  $C = 2.0\%$  than when  $C = 1.0\%$ .

Figures 6 and 7 reveal specific gas holdup changes as a function of fiber mass fraction. According to both figures, gas

holdup is not significantly affected by fiber mass fraction when  $C < 0.4\%$ . But when  $0.4\% \leq C \leq 1.0\%$ , gas holdup declines sharply with increasing  $C$ . When  $1.2\% \leq C \leq 1.5\%$ , the gas holdup decline is less severe with increasing  $C$ , and in some cases, negligible. At  $U_g = 20$  cm/s,  $\varepsilon$  decreases with  $C$  in the same manner for all  $U_l$ , indicating a negligible influence of  $U_l$  on the effects of fiber mass fraction at high superficial gas velocities. When  $U_g = 5$  cm/s and  $C \geq 1.0\%$ , all gas holdup values converge. Figure 7 shows the shape of the  $\varepsilon$ - $C$  curve is not affected by superficial gas velocity except at very low values ( $U_g = 2$  cm/s), where gas holdup is nearly constant for the range of fiber mass fractions in this study.

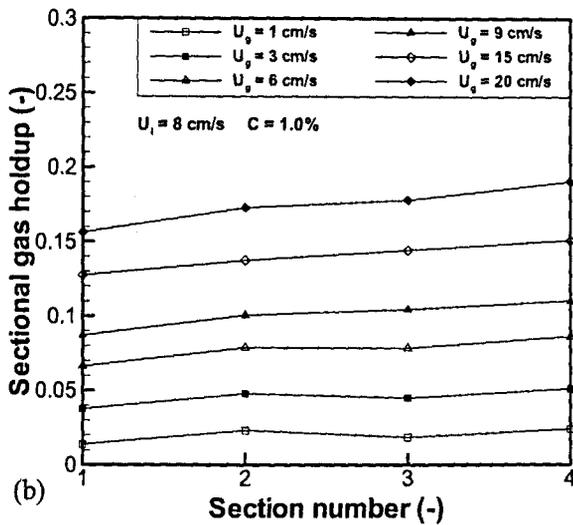
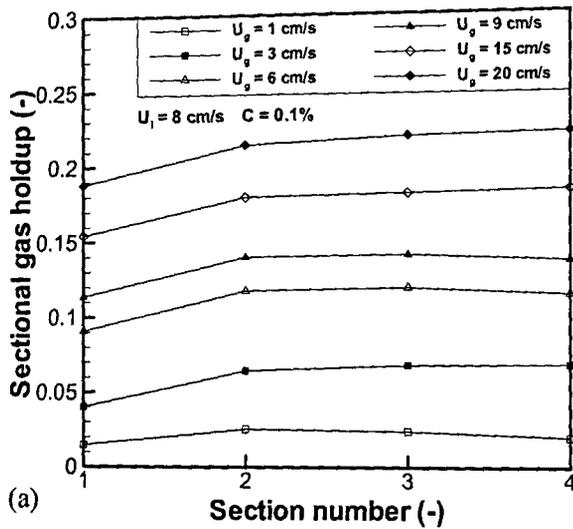


Figure 8. Axial gas holdup variation at different superficial gas velocities ( $U_l = 8$  cm/s); (a)  $C = 0.1\%$ , (b)  $C = 1\%$ .

#### Axial Gas Holdup Variation

Figure 8a shows the sectional average gas holdup distribution at  $U_l = 8$  cm/s and  $C = 0.1\%$ . There is not a significant difference between the sectional average gas holdups in the top 3 sections, but the average gas holdup in the bottom section is significantly lower. The profile is not significantly affected by  $U_g$ . This agrees with the visual observation that in the bottom section, especially in the region right above the sparger, bubbles flow upward fast with paths less tortuous than those in the top 3 sections, where gas backmixing is significant, which enhances the bubble residence time. However, as shown in Fig. 8b, when  $C = 1.0\%$  ( $U_l = 8$  cm/s), the sectional average gas holdup increases with height from the bottom section to the top section, and this trend is more significant when  $U_g$  is higher. This agrees with Lindsay et al. [5] and Schulz and Heindel [6] and can be explained by column recirculation and bubble entrainment from the column exit, which is significant when  $C = 1.0\%$  but less so when  $C =$

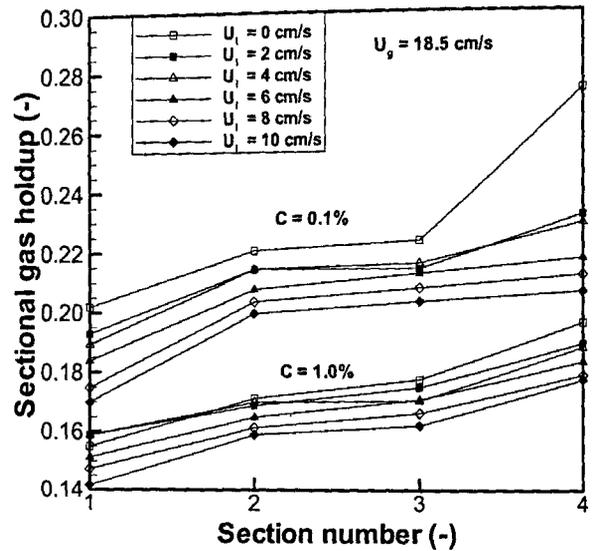


Figure 9. Axial gas holdup variation at different superficial liquid velocities ( $U_g = 18.5$  cm/s).

0.1%. When large bubbles exit the column, the liquid surface is violently disturbed and small bubbles are entrained in the liquid and are carried downward with backmixed liquid. This effect decreases with decreasing column height due to bubble coalescence and rise, and increases with increasing  $U_g$  because larger bubbles enhance backmixing.

Figure 9 presents the distribution of sectional average gas holdup at different superficial liquid velocities when  $U_g = 18.5$  cm/s and  $C = 0.1\%$  or  $1.0\%$ . At  $C = 0.1\%$  and  $U_l = 0$  cm/s,  $\varepsilon_4$  is much higher than the sectional average gas holdups in the lower sections ( $\varepsilon_1, \varepsilon_2, \varepsilon_3$ ); this trend is still significant when  $U_l = 2$  cm/s and 4 cm/s. This gas holdup increase is the result of the large voids that are formed when large bubbles are released at the top of the column. The voids temporarily reduce the liquid surface in the bubble column to a height below pressure transducer  $P_5$  for a time period that decreases with increasing  $U_l$ . When  $U_l \leq 4$  cm/s, the time period is long enough to produce a significant error in  $\varepsilon_4$  due to the liquid height being below  $P_5$ . When  $U_l \geq 6$  cm/s, the voids can be quickly filled by the liquid upflow, making the error less significant. The difference between  $\varepsilon_1$  and  $\varepsilon_2$  significantly increases with increasing  $U_l$  due to shorter bubble residence time in section 1 at higher  $U_l$ . At  $C = 1.0\%$ , continuous fiber networks form and make the bubble paths tortuous at section 1. As a result, the difference between the bubble residence time in section 1 and section 2 is less significant at all  $U_l$ , thus the increase of the difference between  $\varepsilon_1$  and  $\varepsilon_2$  with increasing  $U_l$  is less significant. In section 4,  $\varepsilon_4$  is only slightly higher than  $\varepsilon_3$  and it follows the general trend of increasing gas holdup with column height at higher fiber mass fractions. Additionally, visual observations reveal  $P_5$  is seldom exposed to air when  $C = 1\%$ , which is not the case when  $C = 0.1\%$ .

## Gas Flow Regime Transition

In this section, the drift-flux model [17] is used to identify the gas flow regime transitions. This model accounts for the radial nonuniformity of flow and holdup profiles typically encountered in the heterogeneous flow regime. The drift-flux is defined as the difference between the velocity of a bubble and the average volumetric flux density of the gas-liquid mixture. It is assumed to be independent of gas holdup and equal to the terminal rise velocity of a single bubble in an infinite medium. For a cocurrent bubble column, it can be shown that [18]

$$\frac{U_g}{\varepsilon} = C_0(U_g + U_l) + U_{b\infty} \quad (2)$$

where  $C_0$  is a distribution parameter gauging the radial velocity and holdup profile uniformity and  $U_{b\infty}$  is the terminal rise velocity of a single bubble in an infinite medium.  $C_0$  and  $U_{b\infty}$  can be found by plotting  $U_g / \varepsilon$  as a function of  $(U_g + U_l)$ .

Zahradnik et al. [18] observed that changes of slope in the drift-flux plot indicate changes in flow regime. Xie et al. [7] showed that the Zuber-Findlay model could successfully model the gas holdup data in a cocurrent air-water-pulp fiber bubble column when the flow regime is other than dispersed bubbly flow or layered bubbly flow. Using this method, Su and Heindel [10] demarcated the superficial gas velocities at which flow regime transitions occurred in a 15.24 cm semi-batch air-water-Rayon fiber bubble column.

Equation (2) can be rewritten as

$$\frac{U_g}{\varepsilon} = C_0 U_g + (C_0 U_l + U_{b\infty}) = C_0 U_g + B_0 \quad (3)$$

where  $B_0 = C_0 U_l + U_{b\infty}$  is a constant for a given flow regime and  $U_l$ . We can plot  $U_g / \varepsilon$  versus  $U_g$  and get the same slope as the  $U_g / \varepsilon$  versus  $(U_g + U_l)$  plot for the same flow conditions.

Thus, we can use the  $U_g / \varepsilon$  versus  $U_g$  plot to identify the transitional superficial gas velocity at a given  $U_l$ .

Figure 10 shows the effect of  $U_l$  on  $U_g / \varepsilon$  as a function of  $U_g$  at low ( $C = 0.1\%$ ) and high ( $C = 1.0\%$ ) fiber mass fractions. When  $C = 0.1\%$ , as shown in Fig. 10a, each of the  $U_g / \varepsilon$  versus  $U_g$  curves for different  $U_l$  can be divided into 3 regions according to their slope. According to visual observations and the flow regimes described by Reese et al. [9], the three regions correspond to dispersed bubble flow (region a), vortical-spiral flow (region b), and turbulent flow (region c). Each of the three regions on one of the  $U_g / \varepsilon$  versus  $U_g$  curves has the same slope as the counterparts on the other curves. The two superficial gas velocities at which both regime transitions occur as  $U_g$  increases at one fixed  $U_l$  are very close to those at other superficial liquid velocities. At each of the superficial liquid velocities, the transition from dispersed bubble flow to vortical-spiral flow occurs at about  $U_g = 4$  cm/s, while the transition from vortical-spiral flow to turbulent flow occurs at about  $U_g = 13\sim 14$  cm/s. The slope of the vortical-spiral flow regime is slightly different from that of the turbulent flow regime while

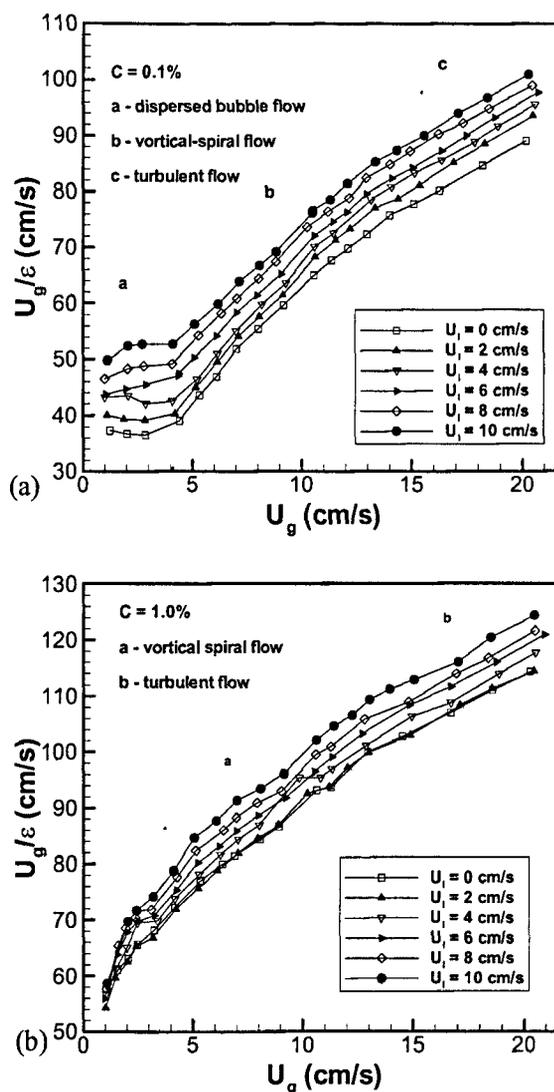


Figure 10. Variation of  $U_g / \varepsilon$  with superficial gas velocity at different superficial liquid velocities; (a)  $C = 0.1\%$ , (b)  $C = 1.0\%$ .

both of them are distinctly different from that of the dispersed bubble flow regime. The superficial liquid velocity only influences the intercept at  $U_g = 0$ , which is consistent with Eq. (3).

When  $C = 1.0\%$ , as shown in Fig. 10b, the dispersed bubble flow does not appear. There is only one regime transition on the curves, which occurs at about  $U_g = 13\sim 14$  cm/s, regardless of  $U_l$ . When  $U_g > 5$  cm/s, the slope of region a and region b are independent of  $U_l$  and very close to those of region b and c in Fig. 10a, respectively, suggesting that the corresponding flow regimes at  $C = 1.0\%$  are vortical-spiral flow and turbulent flow. However, when  $U_g < 5$  cm/s and  $U_l > 0$  cm/s, the slopes increase with  $U_l$  and are greater than the slope at higher  $U_g$ . This is attributed to the gas holdup measurement error due to shear friction, which increases with

$U_l$  and  $C$  and becomes significant only at low  $U_g$  in high fiber mass fraction suspensions. This is consistent with the fact that the slope of the curve at  $U_l = 0$  cm/s does not change at  $U_g < 5$  cm/s.

Figure 11 shows the effects of fiber mass fraction on gas flow regime transitions when  $U_l = 8$  cm/s; similar results are found at other superficial liquid velocities. When  $C = 0.1\%$  or  $0.2\%$ , the  $U_g / \varepsilon$  versus  $U_g$  curves overlap with the curves at  $C = 0\%$ . Both slopes and intercepts of the curves are independent of  $C$ . When  $C$  is increased to  $0.4\%$ , the  $U_g / \varepsilon$  versus  $U_g$  curve is still parallel to the curves of lower fiber mass fractions at every  $U_g$ . Only the intercepts of the curve are changed. It is clear that there are three gas flow regimes when  $C \leq 0.4\%$ , i.e., dispersed bubble flow, vortical-spiral flow, and turbulent flow. In fiber suspensions with  $C \leq 0.4\%$ , the superficial gas velocity at which the gas flow regime transitions from dispersed bubble flow (vortical-spiral flow) to vortical-spiral flow (turbulent flow) is about 4 cm/s (13.5 cm/s). When  $0.6\% \leq C \leq 1.5\%$ , only the vortical-spiral flow and turbulent flow regimes appear, and the superficial gas velocity at which transition occurs is 13–14 cm/s, with the lower  $U_g$  corresponding to the higher  $C$ . The disappearance of the dispersed bubble flow regime when  $C > 0.6\%$  is attributed to the enhancement of bubble coalescence by the fiber network. This is consistent with the observations of Reese et al. [9] and Heindel [12] in semi-batch bubble columns. When  $U_g \geq 5$  cm/s, the slopes of the  $U_g / \varepsilon$  versus  $U_g$  curves are not significantly different from those at  $C \leq 0.4\%$ . The exception to this is the  $C = 2\%$  data set, which does not follow any trend due to the increased air entrainment with increasing  $U_g$ . The separation distance between neighboring  $U_g / \varepsilon$  versus  $U_g$  curves varies nonuniformly with  $C$ , suggesting that the intercept  $B_0$  in Eq. (3) is a nonlinear function of  $C$ . When  $U_g \lesssim 5$  cm/s and  $C > 0.4\%$ , the slope increases with increasing  $C$  because of the gas holdup measurement error due to wall shear friction, which increases as fiber mass fraction increases at low superficial gas velocities.

## CONCLUSIONS

This study examined the effects of superficial liquid velocity, superficial gas velocity, and fiber mass fraction on the gas holdup and flow regime transition in well-mixed water-fiber suspensions in a 15.24 cm cocurrent bubble column. Experimental results showed that the gas holdup decreases linearly with increasing superficial liquid velocity when fiber mass fraction and superficial gas velocity are constant. The gas holdup was not significantly affected by fiber mass fraction in the range of  $C < 0.4\%$ , but decreased with  $C$  in the range of  $0.4\% \leq C \leq 1.5\%$ . When  $C > 1.5\%$ , a significant amount of air was entrained in the fiber suspension and circulated with the water-fiber slurry in the system; as a result, the measured gas holdup was higher than that at  $C = 1.5\%$ . The axial gas holdup

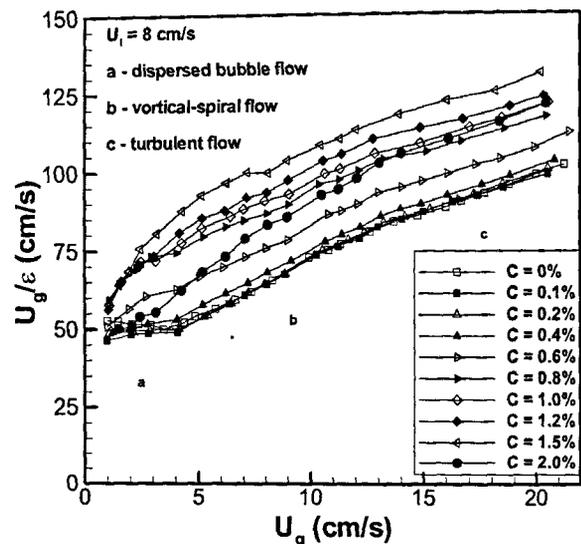


Figure 11. Variation of  $U_g / \varepsilon$  with superficial gas velocities at different fiber mass fractions ( $U_l = 8$  cm/s).

distribution was shown to be a complex function of  $U_g$ ,  $U_l$ , and  $C$ . The drift-flux model was used to analyze the flow regime transitions at different operating conditions. Three distinct flow regimes, i.e., dispersed bubble flow, vortical-spiral flow, and turbulent flow were observed when  $C \leq 0.4\%$ , but only the latter two regimes were identified when  $0.6\% \leq C \leq 1.5\%$ . The critical superficial gas velocities at which the regime transitions occurred were not significantly affected by  $U_l$  and slightly decreased with  $C$ .

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