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EFFECT OF GAS DISTRIBUTOR ON GAS HOLDUP IN FIBER SUSPENSIONS

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ABSTRACT

Two different aeration plates are used to study their effect on gas holdup and flow regime transition in fiber suspensions. Two gas distributors with different open areas (A = 0.57% and 2.14%) and the same orifice diameter (d_o = 1 mm) are used, and experiments are performed using three different Rayon fiber lengths (L = 3, 6, and 12 mm) over a range of superficial gas velocities ($U_g \leq 18$ cm/s) and a range of fiber mass fractions ($0 \leq C \leq 1.8\%$) in a 15.24 cm diameter semi-batch bubble column. Experimental results show that the distributor with A = 2.14% tends to produce lower gas holdup than the one with A = 0.57% for both air-water systems and fiber slurries. However, the effect of distributor open area on gas holdup diminishes at high fiber mass fractions ($C \geq 1.2\%$). Both distributors generate homogeneous, transitional, and heterogeneous flow regimes over the range of superficial gas velocities for air-water and low fiber mass fraction suspensions. However, the distributor with A = 2.14% enhances the flow regime transition, i.e., the superficial gas velocity at which the transitional flow regime appears is lower. Additionally, the fiber mass fraction at which purely heterogeneous flow is observed is lower when A = 2.14%.

Keywords: Bubble column; Drift flux; Gas holdup; Gas distributor; Fiber suspension; Flow regime.

NOMENCLATURE

A	open area, %
C	fiber mass fraction, %
d_o	orifice diameter, mm
H	column height, m
L	fiber length, mm
M_f	dry fiber mass, kg
M_t	total mass of fiber-water mixture, kg
P	pressure of the air-water-fiber suspension, Pa
P_o	pressure of the water-fiber suspension, Pa
t_f,	time of bubble formation
t_i	time for a bubble, growing to a diameter equal to the inter-orifice distance, to begin interaction
t_s	time to drain the liquid film to a critical thickness to rupture
U_g	superficial gas velocity, cm/s
V	Volume of the fiber-water mixture, m^3
v_o	orifice gas velocity, cm/s
We	Weber number

Greek letters

ε	gas holdup
ρ_{eff}	effective density of the fiber-water mixture, kg/m^3
ρ_g	gas density, kg/m^3
ρ_f	dry fiber density, kg/m^3
ρ_w	water density, kg/m^3
σ	surface tension, mNm^{-1}

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INTRODUCTION

Bubble columns are commonly used to affect gas-liquid (GL) or gas-liquid-solid (GLS) heat and/or mass transfer operations. Considerable attention has been paid to the study of liquid (slurry) properties, the gas distributor, and bubble column dimensions on bubble column gas holdup, also termed the volumetric gas fraction or void fraction. Selected studies on the liquid (slurry) property effects include surface tension [1, 2], viscosity [3-6], and solid type and loading [7-11].

Gas-liquid-fiber (GLF) systems, where fibers comprise the solid phase, have grown in interest due to their applications in the pulp and paper industry, including paper recycling (i.e., flotation deinking), fiber bleaching, direct-contact steam heating, and deaeration. Numerous gas-liquid-fiber studies have been devoted to gas holdup [12-17], flow regimes [14, 18, 19], and bubble size distribution [20].

The gas distributor is a key factor that ensures an even inlet gas distribution, which provides the highest gas holdup and thus, the largest possible interfacial area for heat/mass transfer. Hence, the geometric properties of the distributor plate are very important to bubble column performance. Open area, defined as the ratio of the total plate hole area to column cross-sectional area, is related to the size and number of aeration holes in a perforated plate distributor and is one parameter that may have a significant effect on gas holdup.

Contradictive phenomena of the effect of open area are observed in the literature. Zahradnik et al. [3], Ohki and Inoue [21], Tsuchiya and Nakanishi [22], and Zahradnik and Kastanek [23] found that gas holdup increases with increasing plate open area (i.e., by increasing the number of holes). This is attributed to the lower bubble velocity at the inlet hole with increasing open area, resulting in a lower liquid circulation, which has a favorable effect on the stability of the homogeneous flow regime. On the contrary, Shnip et al. [24] numerically showed that gas holdup decreases with increasing open area. The results in the current work also show that the gas holdup with A = 0.57% is higher than that of A = 2.14% and indicates that some other factors may be combined with open area affecting the bubble formation size and distribution.

Assuming holes are uniformly distributed over the entire aeration plate, a change in open area leads to the change in the orifice spacing, which has an impact on the bubble-bubble interaction when bubbles are formed at the orifice and the resulting gas holdup. Kawasaki and Tanaka [25] investigated the effect of hole pitch with a constant number of holes on gas holdup and observed that gas holdup decreased with decreasing hole pitch. This was attributed to the fact that when the hole pitch was smaller, bubbles tended to coalesce together as soon as they left the orifice, resulting in larger bubble sizes and a lower gas holdup. Bubble formation at closely spaced orifices was studied by Solanki et al. [26]. They pointed out that close spacing enhanced bubble coalescence at orifices.

Orifice spacing plays an important role in the inlet gas distribution, and the quality of the inlet gas distribution directly influences the interfacial area and transport rate in bubble column reactors [23]. Zahradnik and Kastanek [27] found that a uniform gas distribution leads to higher gas holdup compared to a non-uniform gas distribution.

Orifice spacing influences the inlet gas distribution through affecting bubble formation at the orifice, in which two modes exist: (i) synchronous, where bubbles are formed simultaneously through each orifice, producing a uniform gas holdup profile in the bottom of the column; and (ii) asynchronous, where the active orifices work either out of phase (bubbles are in different stages of formation at the same time) or alternate (some orifices are not active) [28, 29]. Ruzicka et al. [28] demonstrated that orifice spacing plays a key role in the modes of bubble formation. Bubble formation modes are also influenced by the gas flow rate. Ruzicka et al. [29] showed that there is a critical gas flow rate beyond which the synchronous regime begins to lose its stability and accelerates the transition from homogeneous flow to heterogeneous flow. This critical gas flow rate is a function of orifice spacing, and decreases with decreasing orifice spacing.

In addition, open area combined with gas flow rate is a decisive factor that ensures the stable performance of the gas distributor, leading to a uniform gas distribution. Haug [30] investigated the stability of perforated plates and claimed that in order to get an even gas distribution, the plate pressure drop must be above some critical value; the pressure drop is related to the gas flow rate and the plate open area. There is a limiting gas flow rate below which the gas distribution is non-uniform and liquid weeping will occur. This causes the gas distribution to change from even to uneven as the plate open area increases.

The effect of gas distributor open area on gas holdup in gas-liquid systems has been studied extensively, but little information is available for gas-liquid-solid systems. This study will address the effect of aeration plate open area (A = 0.57% and 2.14%) on gas holdup in gas-liquid-fiber systems.

EXPERIMENTAL PROCEDURES

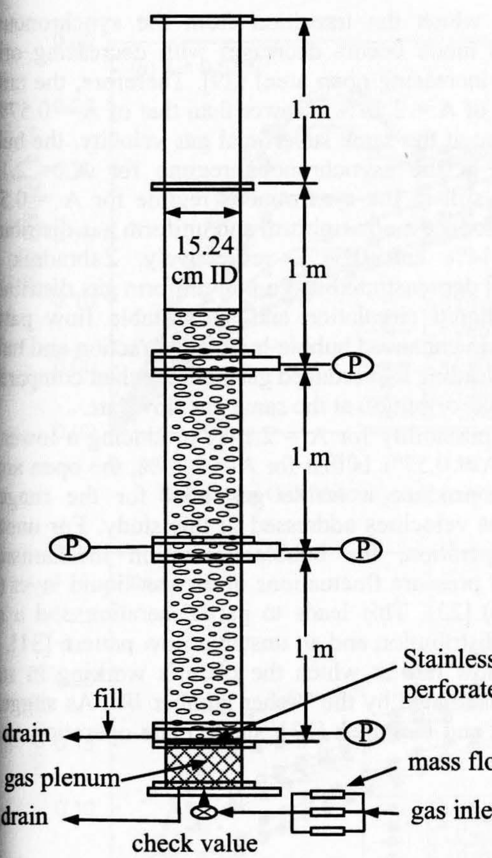
The bubble column experimental facility used in this study is schematically represented in Fig. 1. The bubble column consists of four 1-m sections of 15.24 cm ID cast acrylic, yielding a total column height of 4 m. Gas is injected at the base of the column through one of two stainless steel perforated plates. Two distributor plates with different open areas (A = 0.57% and 2.14%) are used (Fig. 2). For each plate, 1-mm diameter holes are uniformly distributed over the entire plate, and the change in open area is produced by changing the number of holes. A gas plenum is located below the perforated plate and is filled with glass beads to promote uniform gas distribution into the test facility. Three mass flow meters are used to measure the gas flow rate to encompass a low, medium, and high gas flow rate range, and a check valve prevents liquid backflow into the mass flow meters. Four pressure transducers are installed along the column, one located at the column base, two at H = 1 m, and one at H = 2 m, where H is the column height from the perforated plate. The mass flow meters and pressure transducers are interfaced to a data acquisition system.

The GLF system is composed of air, water, and Rayon fiber. Three nominal lengths of Rayon fiber are studied in this paper (L = 3, 6, and 12 mm) and the fiber diameter is 20.6 μm. Various fiber mass fractions ($0 \leq C \leq 1.8\%$) and superficial gas velocities ($U_g \leq 18$ cm/s) are investigated. The superficial liquid velocity in this study is held constant at zero.

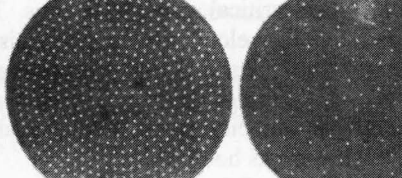
The gas holdup (ε) is measured in the upper column section ($1 \leq H \leq 2$ m), where it is assumed bubble behavior is not influenced by the distributor region (near the column base). The gas holdup is determined from the column pressure drop. In a semi-batch system, the frictional pressure drop is negligible, so the total pressure drop corresponds to the hydrostatic head; in this case,

$$\varepsilon = 1 - \frac{\Delta P}{\Delta P_o} \tag{1}$$

where ΔP is the pressure drop between any two pressure transducers with $U_g > 0$, and ΔP_o is the corresponding pressure drop with $U_g = 0$. For the GL system, ΔP_o equals the liquid hydrostatic head; for the GLF system, ΔP_o corresponds to the fiber slurry hydrostatic head.



gure 1. Experimental bubble column.



gure 2. Gas distributor plate; (a) A = 2.14%, (b) A = 0.57%.

Experiments are performed at specified fiber mass ctions (C), where the actual fiber mass added to the system is termined from

$$M_f = CM_t \quad (2)$$

he total mass of the fiber-water mixture M_t is determined from $M_t = \rho_{eff}V$, where ρ_{eff} is the effective slurry density determined om

$$\frac{1}{\rho_{eff}} = \frac{C}{\rho_f} + \frac{1-C}{\rho_w} \quad (3)$$

d the moisture-free Rayon fiber density is $\rho_f = 1500$ kg/m^3 d V is the volume of the fiber-water mixture.

Before an experiment is initiated, the dry fiber mass lculated from Eq. (2) is washed using tap water for 2-3 times remove any residual contaminants, and soaked in tap water for 2-3 days to remove additives absorbed on the fiber surface. The soaked fiber is then added to a small container of water and mixed at low speed using an electronic mixer equipped with a propeller blade. The resulting mixture is then added to the bubble column which is partially filled with water. Additional water is added to fill the column to a height of 2.13 m (14 column diameters). All experiments are initiated with this slurry volume. The column is then operated at a high gas flow rate for approximately 35 minutes to ensure the slurry was well mixed throughout the column. The gas flow rate is then reduced to the lowest value of interest to begin data collection and then incremented sequentially for additional data points. Note that data are collected approximately 15 minutes after each gas flow rate adjustment. The gas used in all experiments is filtered compressed air.

RESULTS AND DISCUSSION

Air-Water

The effect of gas distributor open area on gas holdup in an air-water system is shown in Fig. 3 (open symbols). At low and high gas flow rates, where the corresponding flow regime is homogeneous and heterogeneous, respectively, the open area has negligible effect on gas holdup. This phenomenon agrees with the observations of Zahradnik et al. [3] and Zahradnik and Kastanek [23]. In the heterogeneous flow regime, gas holdup is determined by bulk liquid circulation, and is hardly affected by bubble formation modes [3], leading to little gas holdup difference between the two plates in this regime. At medium gas flow rates, where the gas flow is in the transitional regime, gas holdup behavior deviates between the two plates, and the gas holdup for A = 0.57% is higher than for A = 2.14%. In the transitional flow regime for A = 0.57%, gas holdup increases with increasing superficial gas velocity until a maximum gas holdup is reached, and then gas holdup decreases with increasing superficial gas velocity to a minimum value which indicates the end of the transitional flow regime. For A = 2.14%, no maximum gas holdup is observed, and the gas holdup continuously increases with superficial gas velocity.

The gas holdup for A = 0.57% is higher than that of A = 2.14% in the transitional flow regime, which contradicts the

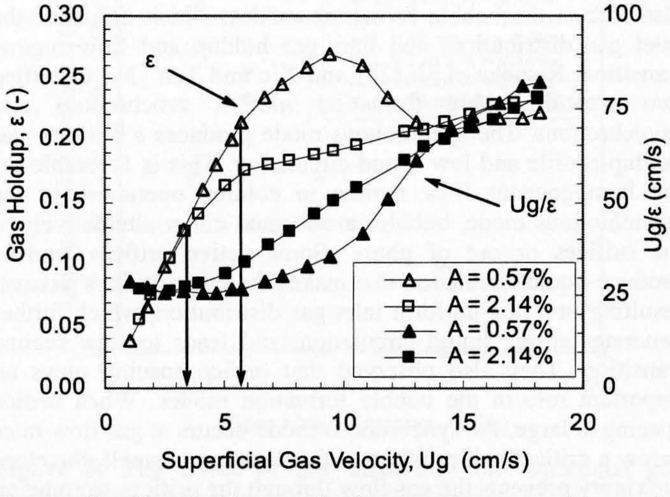


Figure 3. Gas holdup and flow regime transitions for distributors with A = 0.57% and 2.14% in an air-water system.

observation of Zahradnik et al. [3], Tsuchiya and Nakanishi [22], and Zahradnik and Kastanek [23]. They observed that gas holdup increases with increasing open area. However, the distributor open areas used by Zahradnik et al. [3] and Zahradnik and Kastanek [23] were less than or equal to 1%. The observation in this study at A = 2.14% indicates that the favorable effect of open area on gas holdup may be valid only within a certain range; when open area is beyond this range, it will reduce gas holdup.

A larger open area may enhance bubble coalescence, which contributes to the reduction of gas holdup. At the same superficial gas velocity, the bubble velocity through the orifice is reduced with increasing open area, leading to a lower degree of liquid circulation, which results in higher gas holdup and delays the flow regime transition. However, further increasing open area beyond a critical value will enhance bubble coalescence at the orifices due to the reduced orifice spacing, which leads to the reduction of gas holdup. Increasing the open area by increasing the number of orifices with a constant orifice diameter implies a decrease in orifice spacing, which enhances bubble coalescence. Solanki et al. [26] proposed that coalescence of adjacent bubbles formed at closely spaced holes may occur and depend on three time factors: (i) time of bubble formation (t_f), (ii) time required for a bubble growing to a diameter equal to the inter-orifice distance to begin interaction (t_i), and (iii) time to drain the liquid film to a critical thickness to rupture (t_s). For $t_f > t_i + t_s$, coalescence occurs. Smaller orifice spacing leads to the smaller bubble size required for the occurrence of interaction with adjacent bubbles. Thus, provided the bubble growth rate is constant, smaller orifice spacing results in smaller t_i and $t_i + t_s$, which leads to the higher possibility of coalescence compared to larger orifice spacing. Enhanced bubble-bubble interaction with decreasing orifice spacing was observed by Xie and Tan [31]. Additionally, when formed through holes, bubble diameter increases with increasing gas flow rate; hence, the probability of bubble-bubble interaction increases with increasing gas flow rate. Therefore, when the superficial gas velocity is increased, the likelihood of bubble coalescence is higher for A = 2.14% than for A = 0.57%. As a result, the gas holdup for A = 2.14% is lower than that of A = 0.57%.

The change in orifice spacing with increasing open area also affects the bubble formation modes, which influence the inlet gas distribution, and thus gas holdup and flow regime transition. Ruzicka et al. [28] and Xie and Tan [31] identified two typical bubble formation modes, synchronous and asynchronous. The synchronous mode produces a uniform gas holdup profile and low liquid circulation. This is favorable for the homogeneous flow regime in column operation. In the asynchronous mode, bubbles are formed either alternatively at the orifices or out of phase. Some active orifices tend to produce liquid circulation that makes the other orifices passive, resulting in a non-uniform inlet gas distribution, which further generates strong liquid circulation, and leads to flow regime transition. They also observed that orifice spacing plays an important role in the bubble formation modes. When orifice spacing is large, the synchronous mode occurs at gas flow rates below a critical value. When orifice spacing is small, the close proximity prevents the gas flow through the orifices from being in phase and no synchronous mode is observed. The critical gas flow rate at which the transition from the synchronous to asynchronous mode occurs decreases with decreasing orifice spacing (i.e., increasing open area) [29]. Therefore, the critical gas flow rate of A = 2.14% is lower than that of A = 0.57%. It is possible that at the same superficial gas velocity, the bubble formation is in the asynchronous regime for A = 2.14%, whereas it is still in the synchronous regime for A = 0.57%. This would produce a non-uniform and uniform gas distribution for A = 2.14% and 0.57%, respectively. Zahradnik and Kastanek [27] demonstrated that a non-uniform gas distribution will induce liquid circulation and an unstable flow pattern, which results in enhanced bubble-bubble interaction and bubble coalescence, leading to a reduced gas holdup when compared to a uniform gas distribution at the same gas flow rate.

Another possibility for A = 2.14% producing a lower gas holdup than A = 0.57% is that for A = 2.14%, the open area is too large to produce a stable gas inlet for the range of superficial gas velocities addressed in this study. For unstable distributor operation, the bubble formation mechanism is influenced by pressure fluctuations in the gas-liquid layer (i.e., bubbling bed) [23]. This leads to partial aeration and a non-uniform gas distribution and an unstable flow pattern [31]. The critical gas flow rate at which the plate is working in stable operation is estimated by the Weber number We. As suggested by Zahradnik and Kastanek [23], stable plate operation occurs when

$$We = \frac{v_o^2 d_o \rho_g}{\sigma} \geq 2 \tag{4}$$

where v_o is the orifice gas velocity, d_o is the orifice diameter, ρ_g is the gas density, and σ is the surface tension. To achieve the critical orifice Weber number, a larger gas flow rate is required for a larger open area. If $We = 2$, $d_o = 1$ mm, $\rho_g = 1.57$ kg/m^3, and $\sigma = 72.7$ mNm^{-1}, the critical v_o is 96.2 cm/s. Thus, the corresponding superficial gas velocity in our system is 5.4 cm/s and 20.6 cm/s for A = 0.57 % and 2.14%, respectively. Thus, the plate with A = 2.14% can not work in stable operation for the entire superficial gas velocity range of this study, which may contribute to the lower gas holdup.

Figure 3 also shows the flow regime transitions for A = 2.14% and 0.57% by applying the drift flux model proposed by Zuber and Findlay [32] (solid symbols). Both plates produce homogeneous, transitional, and heterogeneous flow regimes. For the homogeneous flow regime, U_g/ε slightly decreases with increasing U_g and reaches a minimum value denoted as the critical superficial gas velocity at which transitional flow appears. Similar observations were obtained by Tsuchiya and Nakanishi [22]. The negative slope of the plot of U_g/ε vs. U_g in the homogeneous regime for both distributors may be the result of the gas distribution not being uniform, leading to liquid circulation, even at low superficial gas velocities [24]. The liquid circulation reduces bubble rise velocity, leading to a bubble rise velocity less than the terminal rise velocity. This reduction in bubble rise velocity increases with increasing gas holdup (i.e., increasing superficial gas velocity) [24]. Since U_g/ε is denoted as bubble rise velocity [32], U_g/ε decreases with increasing superficial gas velocity.

When the superficial gas velocity is further increased, bubble-bubble interaction is enhanced, and bubble coalescence occurs, which indicates the flow regime transition. In this

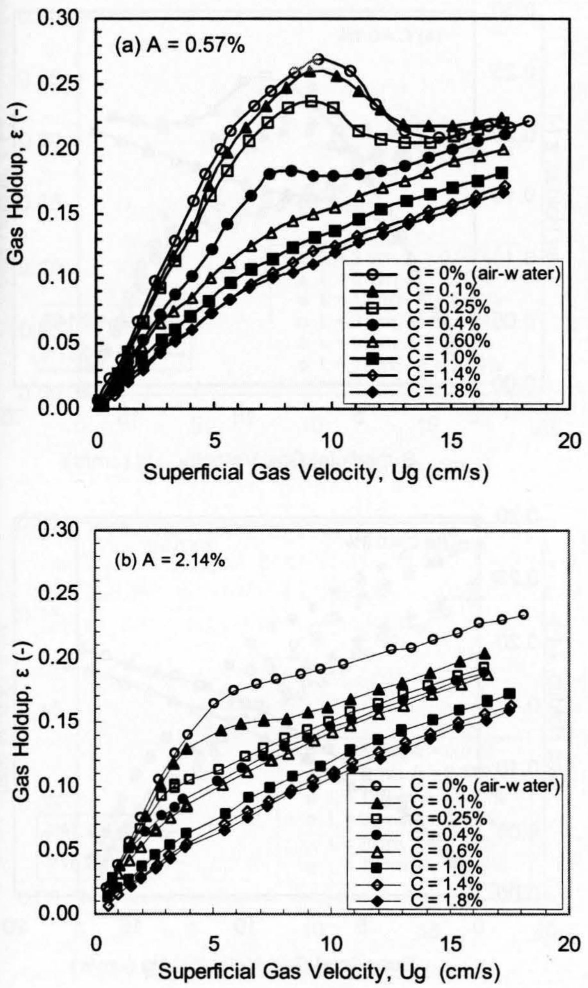


Figure 4. The effect of fiber mass fraction on gas holdup using two different gas distributor plates and L = 3 mm; (a) A = 0.57%, (b) A = 2.14%

regime, gross liquid circulation, increasing with increasing superficial gas velocity, changes the slope of U_g/ε vs. U_g to increase with increasing U_g.

The transitional superficial gas velocity, identified by the down arrows in Fig. 3, is ~3.4 cm/s for A = 2.14%, which is less than ~5.7 cm/s for A = 0.57%. The lower superficial gas velocity at which transition occurs when A = 2.14% may be attributed to two affects. First, bubble coalescence is enhanced with closer orifice spacing (large open area), and this induces liquid circulation and triggers flow regime transition. Second, a large open area (close orifice spacing) results in a partially activated aeration plate [29], leading to a non-uniform gas distribution and liquid circulation, promoting flow regime transition.

Fiber Suspensions

EFFECT OF FIBER MASS FRACTION

Typical trends of the effect of fiber mass fraction on gas holdup for using two different gas distributor plates (A = 0.57% and 2.14%) are shown in Fig. 4 for L = 3 mm long Rayon fiber. For both distributors, gas holdup, as expected, decreases with increasing fiber mass fraction. This phenomenon is attributed to the promotion of bubble coalescence due to the increase in effective suspension viscosity with increasing fiber mass fraction. The reduction in gas holdup with increasing fiber mass fraction is more pronounced for low fiber mass fractions. When fiber mass fraction is high ($C \geq 1.4\%$), fiber addition does not significantly affect gas holdup. The decrease in gas holdup with increasing fiber mass fraction has been explained in detail by Su and Heindel [16]. For A = 0.57% and low fiber mass fractions ($C \leq 0.4\%$, Fig. 4a), gas holdup behavior is similar to that of an air-water system: there is a maximum gas holdup, indicating homogeneous, transitional, and heterogeneous flow regimes exist over the range of superficial gas velocities. The effect of fiber mass fraction is more significant in the transitional flow regime, while little influence is observed in the homogeneous flow regime. At $C > 0.4\%$, gas holdup continuously increases with increasing superficial gas velocity, and purely heterogeneous flow is observed.

For A = 2.14% (Fig. 4b), gas holdup increases with increasing superficial gas velocity monotonically for all the fiber mass fractions. At low fiber mass fractions ($C \leq 0.25\%$), the homogeneous flow regime exists at low superficial gas velocities, and when $C > 0.25\%$, only heterogeneous flow appears over the range of superficial gas velocities. Similar to A = 0.57%, gas holdup is not influenced by fiber mass fraction in the homogeneous flow regime, whereas the transitional flow regime is affected by fiber addition. Similar trends are obtained for Rayon fiber with L = 6 mm and 12 mm for both distributors.

Figure 5 shows the effect of fiber mass fraction on the superficial gas velocity at which transitional flow is observed for the two distributor plates. The superficial gas velocity at which transitional flow begins is determined by the drift flux model proposed by Zuber and Findlay [32] and shown by the arrows in Fig. 3. Additional details in this determination can be found in [16]. In general, fiber addition tends to destabilize the homogeneous flow regime, and when the fiber mass fraction is beyond a critical value, only heterogeneous flow is observed

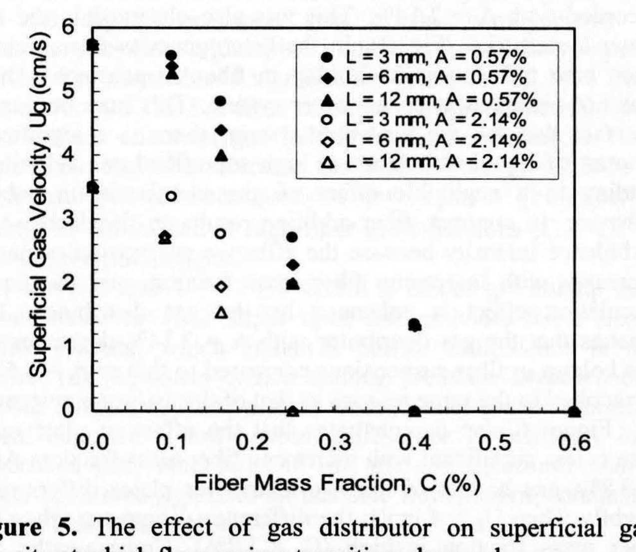


Figure 5. The effect of gas distributor on superficial gas velocity at which flow regime transition observed.

over the entire range of superficial gas velocities. This phenomenon is ascribed to the increase in effective suspension viscosity with increasing fiber mass fraction. Zahradnik et al. [3] have shown that the flow pattern will change from that of the existence of three flow regimes (homogeneous, transitional, and heterogeneous) to purely heterogeneous flow as the liquid viscosity increases. The fiber length has an effect on flow regime transition for both distributors; the longer the fiber, the lower the superficial gas velocity at which transition begins.

It is apparent that the distributor with A = 2.14% encourages the flow regime transition and the transitional superficial velocities for the three fiber lengths are lower than those of A = 0.57%. The critical fiber mass fraction beyond which purely heterogeneous flow regime exists is also dependent on gas distributor. When A = 0.57%, purely heterogeneous flow appears when C $\geq$ 0.6%, and the dependence of the critical fiber mass fraction on fiber length is negligible. When A = 2.14%, the critical fiber mass fraction decreases compared to A = 0.57%, and is affected by fiber length. For L = 3 mm, homogeneous flow is observed when C $\leq$ 0.25%, and for L = 6 mm and 12 mm, this critical value reduces to 0.16%. In addition, when A = 2.14%, the superficial gas velocity at which transition occurs is similar when L = 6 mm or 12 mm, effectively negating the influence of fiber length. Su and Heindel [16] have shown that the fiber mass fraction has more influence on bubble column hydrodynamics than fiber length; Fig. 5 confirms this.

EFFECT OF GAS DISTRIBUTOR OPEN AREA

Figure 6 depicts the effect of gas distributor open area on gas holdup in a fiber suspension. At high superficial gas velocities, the resultant gas holdup when A = 2.14% is lower than that of A = 0.57% at the same fiber mass fraction. At low superficial gas velocities, the distributor has a negligible effect on gas holdup. This phenomenon is similar to that of the air-water system. At low fiber mass fraction (C = 0.1%), where homogeneous, transitional, and heterogeneous flow regimes exist, the gas distributor open area has a significant effect on gas holdup behavior in the transitional gas flow regime, and results in a higher gas holdup when A = 0.57% than that recorded with A = 2.14%. This was also observed in the air-water system (i.e., Fig. 3). In the heterogeneous flow regime, open area influences gas holdup in fiber suspensions, which was not observed in an air-water system. This may be due to the fact that for the air-water system, there is a significant amount of liquid turbulence at high superficial gas velocities, leading to a negligible effect of gas distributor on bubble behavior. In contrast, fiber addition results in the decrease in turbulence intensity because the effective suspension viscosity increases with increasing fiber mass fraction, and the liquid circulation effect is enhanced by the gas distributor. The reasons that the gas distributor with A = 2.14% decreases the gas holdup in fiber suspensions compared to that of A = 0.57% is ascribed to the same reasons as that of the air-water system.

Figure 6 also demonstrates that the effect of plate open area is less significant with increasing fiber mass fraction. At C = 0.8%, gas holdup of the two distributor plates differs only slightly when $U_g \geq 4$ cm/s; the difference disappears when the fiber mass fraction is high (C $\geq$ 1.2%). Consequently, the distributor open area has an effect on gas holdup at low fiber

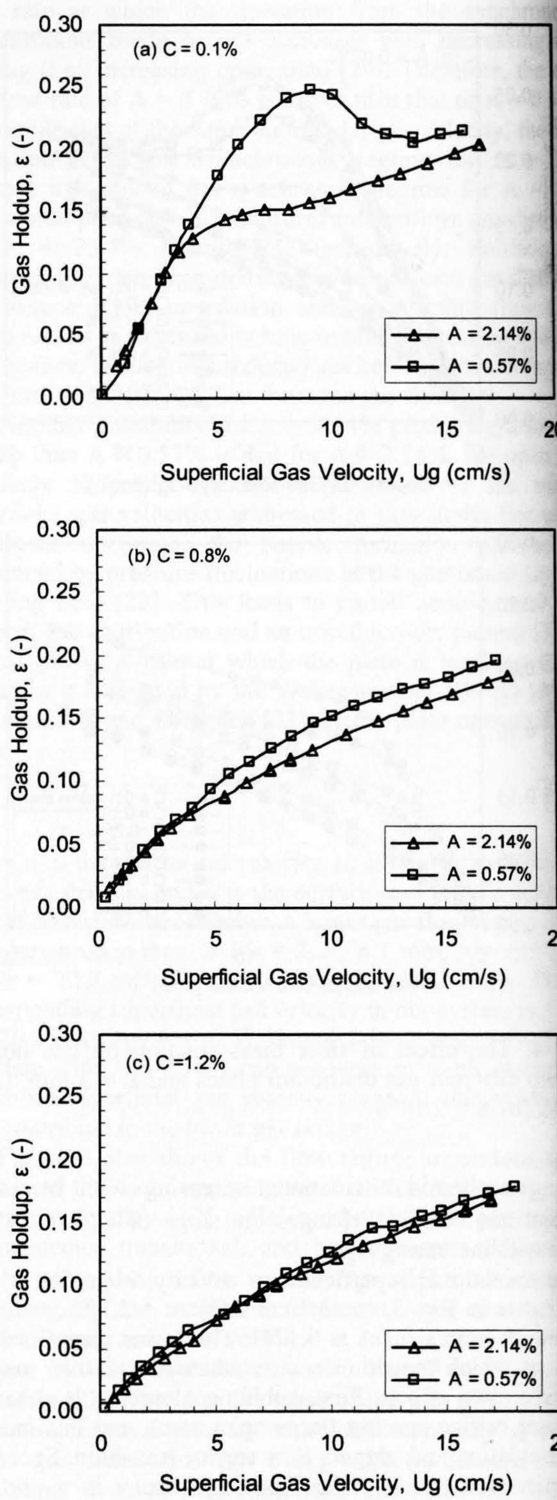


Figure 6. Effect of gas distributor open area on the gas holdup behavior at various fiber mass fractions (L = 3 mm); (a) C = 0.1%, (b) C = 0.8%, and (c) C = 1.2%.

mass fraction suspensions, which depends on gas flow regime. However, in high fiber mass fraction suspensions, distributor open area has a negligible effect on gas holdup.

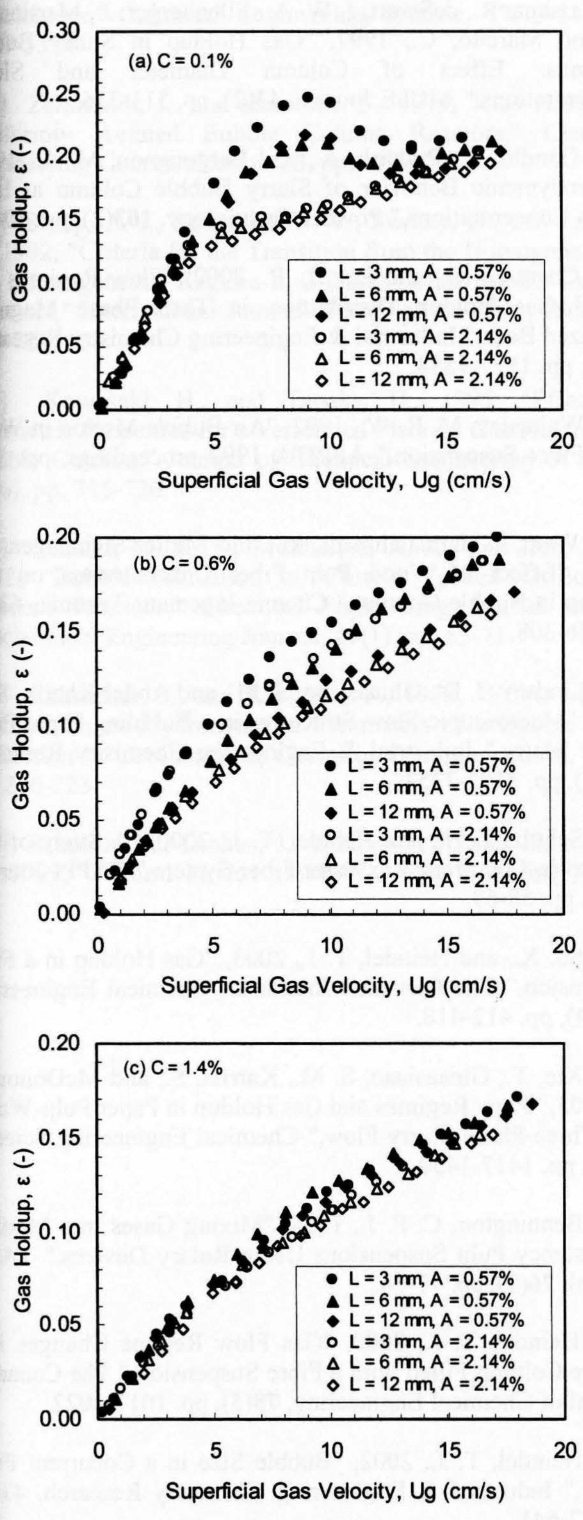


Figure 7. The effect of fiber length on gas holdup; a) C = 0.1%, b) C = 0.6%, and c) C = 1.4%.

EFFECT OF FIBER LENGTH

The effect of fiber length on gas holdup behavior for the two open areas are shown in Fig. 7. At low fiber mass fractions (C = 0.1%) and A = 0.57%, gas holdup decreases significantly when the fiber length is increased from L = 3 mm to L = 6 mm, but a negligible change is observed when the fiber length is further increased to L = 12 mm. In contrast, there is a negligible effect of fiber length on gas holdup when A = 2.14%. At medium fiber mass fractions (C = 0.6%) and A = 0.57%, gas holdup decreases with increasing fiber length; this decrease is only observed between L = 3 mm and L = 6 mm when A = 2.14%. This demonstrates that the influence of fiber length on gas holdup is less important when the gas distributor open area is large. Recall that for a gas distributor with a large open area, asynchronous bubble operation leads to an uneven inlet gas distribution and the gas flow maldistribution results in low gas holdup [27]. Lee et al. [33] found that in gas-liquid-solid systems, the effect of gas flow maldistribution is related to solid density, and the effect is enhanced for lighter particles. As a result, gas holdup reduction is more significant for lighter particles due to the uneven gas distribution. Although different length Rayon fibers have the same density, the tendency of fiber flocculation increases with increasing fiber length [34], leading to an increase in the effective suspension viscosity with increasing fiber length (at constant fiber mass fraction). It is postulated that the fiber length influence on gas holdup is smaller for A = 2.14% because the longer fibers promote a more even gas distribution, offsetting the effect of the gas inlet maldistribution.

Figure 7 also shows that at high fiber mass fractions (C = 1.4%), the two gas distributors produce similar gas holdup results for all three fiber lengths. This indicates that when the fiber mass fraction is high, gas holdup has only a weak dependence on fiber length and gas distributor open area. It also implies that the gas holdup in a high fiber mass fraction suspension is mainly determined by slurry mixing.

CONCLUSIONS

Two gas distributors with different open areas (A = 0.57% and 2.14%) and the same orifice diameter (d_o = 1 mm) were used to study their effect on gas holdup and flow regime transition in Rayon fiber suspensions. When A = 0.57%, a pronounced maximum gas holdup was recorded for the air-water and low fiber mass fraction systems; this was not observed when A = 2.14%. For an air-water system, gas holdup did not depend on open area in the homogeneous or heterogeneous flow regime, but in the transitional flow regime, gas holdup was reduced significantly when A = 2.14% from that of A = 0.57%. For fiber suspensions, gas distributor open area had no effect on gas holdup in the homogeneous flow regime, but tended to decrease gas holdup when A = 2.14% in the transitional and heterogeneous flow regimes. The effect of open area diminished at high fiber mass fractions (C ≥ 1.2%) for all three fiber lengths.

The fact that A = 2.14% tended to reduce gas holdup may be attributed to: (i) a larger open area provides for a closer orifice spacing, which enhances bubble coalescence at the orifice; (ii) the closer orifice spacing promotes asynchronous bubble formation, leading to an uneven inlet gas distribution, liquid circulation, and bubble coalescence at relatively low superficial gas velocities; and (iii) the gas distributor with a larger open area generates an unstable flow pattern, enhancing bubble-bubble interaction.

In general, gas holdup decreased with increasing fiber length when C ≤ 1.4%. This trend was more pronounced when

A = 0.57%. For A = 2.14%, the effect of fiber length is less significant. At high fiber mass fractions, no dependence of gas holdup on fiber length or gas distributor was observed.

Homogeneous, transitional, and heterogeneous flow conditions were observed at low fiber mass fractions for both plates, however, compared to the gas distributor with A = 0.57%, the gas distributor with A = 2.14% tended to destabilize the homogeneous flow regime, and the transitional superficial gas velocity decreased. In addition, the critical fiber mass fraction at which the flow pattern changed from homogeneous, transitional and heterogeneous flow to purely heterogeneous flow was lower when A = 2.14% than when A = 0.57%.

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