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Abstract
Bubble diameter measurements in a two-dimensional cocurrent bubble column are obtained using a gas−liquid−solid system in which the solid component is a cellulose fiber. Flash X-ray radiography, a noninvasive measurement technique, is used to record bubble size in the opaque slurry at various operating conditions. Results are presented for a range of fiber mass fractions ($0 \leq C \leq 1.5\%$), a range of superficial gas velocities ($1 \leq \upsilon_g \leq 4$ cm/s), two superficial liquid velocities ($\upsilon_l = 1$ or 2 cm/s), and two column heights ($H = 15−40$ or $115−140$ cm). Bubbles are categorized as either large ($d_B > 10$ mm) or small ($d_B \leq 10$ mm), and all bubble diameter distributions can be characterized by log-normal distributions. The presence of fibers has the most significant effect on the large bubble size and population, even at mass fractions as low as 0.5%. In general, the large bubble size and population increases with column height, superficial gas velocity, and fiber mass fraction.

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Mechanical Engineering

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Introduction

Gas–liquid and gas–liquid–solid multiphase flows are found in many process industries such as commodity and specialty chemical production, mineral processing, pulp and paper production, and wastewater treatment. These multiphase flows are used to promote solid and/or liquid separation or enhance heat and/or mass transfer operations. A bubble column is one common geometry used to effect these transport processes. Knowledge of the bubble size and bubble size distribution in bubble columns is an important factor because it influences fluid mixing and circulation, heat and mass transfer, and interfacial area. Yang et al.1 recently concluded that “bubble size is a dominating factor affecting the heat transfer rate in slurry bubble columns.” Reilly et al.2 also remark that “bubble diameter and bubble size distribution have been recognized as fundamental variables affecting both the gas holdup and the degree of backmixing in bubble columns.” This paper will focus on bubble size measurements obtained in a rectangular cocurrent bubble column filled with a gas–liquid–solid system in which the solid component is a cellulose fiber at various mass fractions.

Bubble size in a gas–liquid system can be measured by a variety of experimental techniques.3–5 Using photographic techniques, Lin et al.6 showed that bubble size in a gas–liquid system decreases with increasing pressure. Photographic methods were also used by Glasgow et al.7 to measure bubble diameter in an airlift fermentor. They showed that bubble diameter decreased with increasing air flow rate and this was attributed to added turbulence in the system. The presence of electrolytes also reduced the bubble diameter by stabilizing the bubble surface and suppressing bubble coalescence. They further showed that a majority of the bubbles followed a log-normal bubble size distribution.

Ueyama et al.8 measured mean bubble diameter using electric resistivity probes and photographic techniques. They determined that the mean bubble diameter near the wall, determined through photographs, was smaller than that in the bulk fluid, determined by the resistivity probes. Using a nitrogen–molten wax system, Patel et al.9 also concluded that the mean bubble diameter near the wall is not the same as that averaged across the column. Their bubble diameter distributions did, however, fit a log-normal profile. Yu and Kim10 used a fiber optic probe to measure bubble chord lengths and showed they also followed log-normal distributions. Liu et al.11 described a method that transforms local chord length distributions to local bubble size distributions and similar types of distributions result.

The majority of bubble column studies involving solids typically utilize glass, sand, mineral, or coal particles as the solid material. When a solid is added to an air–water system, bubble diameter can be determined photographically by carefully matching indices of refraction.12 Alternatively, thin two-dimensional bubble columns can be used.13–15 X-rays have also been used to measure bubble diameter in opaque multiphase systems.16–18

As with gas–liquid systems, various probes can also be used in gas–liquid–solid systems to determine bubble diameter (chord) distributions. Matsuura and Fan19 determined that bubble diameter distributions in an air–water–glass bead system followed log-normal distributions. This distribution type has also been used by others in similar systems.16,17,20 Although a log-normal bubble diameter distribution appears to be the most commonly used distribution to describe bubble sizes in bubble columns,20 other distributions have also been used.21–23

When the solid phase in a gas–liquid–solid system is composed of a fibrous material, additional complications arise because the fibers typically make the system opaque and they may form entanglements around any probe tip and modify the acquired signal. Cellulose fibers also have a density close to that of water and they can flocculate at mass fractions as low as 0.3% and form continuous fiber networks at mass fractions as low as 1%.24 According to Reese et al.,25 extrapolating conclusions obtained in three-phase systems using spherical low or high-density particles to those using nonspherical low-density particles (i.e., fiber slurries) may not be appropriate.
Hunold et al.,26 measured bubble diameter in dilute cellulose fiber systems with mass fractions less than C = 0.5% by suctioning a small sample out of the test cell and passing it through a capillary tube. Intermittent gas volumes were recorded and translated to equivalent bubble diameters, assuming negligible bubble coalescence in the capillary. Bubble diameter measurements in cellulose fiber slurries have also been obtained by Ajersch et al.27 by isolating fiber samples in a transparent flow cell. When the flow was stopped, the bubbles were allowed to rise to the surface for photographic analysis. This procedure also assumed negligible bubble coalescence, as well as all bubbles were free to rise to the surface. Reese et al.25 used a PIV system to measure bubble diameter in a two-dimensional bubble column filled with a fiber slurry at mass fractions up to C = 0.25%. Higher mass fractions were not addressed due to the inability of the laser light to penetrate the fiber slurry at the higher mass fractions. They did, however, use a fiber optic probe to assess bubble passing frequency and bubble passing period with fiber mass fractions up to C = 1%. They concluded that bubble passing frequency decreased and bubble passing period increased with increasing fiber mass fraction, implying that the bubble population decreased and bubble size increased with increasing fiber mass fraction.

Heindel28 showed that X-ray techniques can be used to record bubble diameter in cellulose fiber slurries and concluded that bubble diameter measurements obtained in a simple gas–liquid system do not represent measurements obtained in a gas–liquid–fiber system, even when the fiber mass fraction is as small as 0.5%. This was further shown by Heindel and Garner29 with cellulose fiber mass fractions as high as 1.5%. In that study, gas bubbles were divided into two categories, large and small. The number of large bubbles increased with increasing fiber mass fraction at the expense of the small bubble population. However, the remaining small bubbles followed the size distribution determined for the small bubbles in a gas–liquid system. It was further shown that the small bubble diameter distribution was independent of fiber mass fraction and well-characterized by a single log-normal bubble diameter distribution. This work was extended using three different cellulose fiber types and similar results were observed.30

This study utilizes flash X-ray radiography to determine bubble diameter in a cocurrent bubble column filled with various air–water–cellulose fiber systems. Fiber mass fractions of 0 ≤ C ≤ 1.5% are investigated over a range of superficial gas velocities (1 ≤ u_g ≤ 4 cm/s), two superficial liquid velocities (u_l = 1 or 2 cm/s), and two column locations (H = 15–40 or 115–140 cm).

**Experimental Procedures**

Figure 1 is a schematic of the cocurrent flow loop. The fluid, which is classified as either water or a water–fiber slurry, is pumped from a 150 L holding tank with a constant output centrifugal pump. Two metering valves control how much fluid returns to a second 150 L holding tank and how much passes through a magnetic flow meter and the bubble column. The fluid enters the bubble column at the column base, exhausts at the column top, and then returns to the second holding tank. Air is also injected at the column base through a fine sintered polyethylene aerator with a nominal pore size of 50 μm. The two holding tanks are connected, and each contains a series of vertical baffles to maximize the fluid retention time in the tanks, allowing air to escape.

The bubble column consists of two 1 m sections with rectangular cross sections of 10 cm × 2 cm and attached end-to-end. The bottom and top of the column contain a channel expansion and contraction region, respectively, to convert pipe flow to channel flow and then back to pipe flow. The entire column is mounted on an adjustable support stand. X-rays are taken of air–water and air–water–fiber slurries at two locations, encompassing column regions H = 15–40 cm and H = 115–140 cm, where H is the column height measured from the column base (Figure 1). These two regions are referred to as the lower and upper column regions, respectively.

The X-ray unit is a 300 keV HP43733A flash X-ray system (Maxwell Physics International, San Leandro, CA), which generates a 30 ns X-ray pulse. The fast X-ray pulse provides stop-motion X-rays of gas bubbles rising through the opaque fluid. The X-ray tube head is mounted in a locking vertical slide to allow X-ray exposures at various column locations. The X-ray aperture is located approximately 2 m from the bubble column, and the tube head is oriented perpendicular to the bubble column face. A single X-ray film cassette, containing a 20 cm × 25 cm X-ray negative, is mounted directly behind the column such that the X-ray aperture is coincident with the film center. Additional details of flash X-ray radiography can be found elsewhere.10,31–34

Once the X-ray images are developed, they are analyzed using image analysis software to determine equivalent bubble diameters, defined as the diameter of a circle whose area is equal to that of the bubble. The minimum recorded bubble diameter in this study is 1 mm, although smaller bubbles may be present in the
system. The majority of the bubbles fall in the diameter range of \( d_b = 2 \text{--} 7 \text{ mm} \). At least six radiographs are analyzed for each test condition. The bubble population in each bubble diameter distribution generally decreases with increasing fiber mass fraction; however, most populations include more than 500 bubbles and over 25\% of the populations contain more than 1000 bubbles. Representative bubble size distributions are presented below; additional bubble size data are reported elsewhere.35,36

Experiments are initially performed in an air–water system (without fiber, \( C = 0 \% \)), composed of compressed and filtered air and city water, to form baseline conditions. The air–water–fiber systems are comprised of city water and one of two cellulose fiber types, either unprinted copy paper (CP) or unprinted old newspaper (ONP). The cellulose fiber is originally soaked for several hours, then reslushed at a mass fraction of approximately 11\%, and finally diluted with city water to the desired mass fraction. A filtrate sample from each suspension was obtained to determine the liquid surface tension. Samples of the cellulose fiber were also analyzed to determine a weight-weighted fiber length and ash content. These results are summarized in Table 1.

As shown in Table 1, copy paper typically has longer fibers and contains more fillers than old newspaper. Additionally, the fibers used to manufacture copy paper are processed differently from those used in newspaper; these processing differences are detailed by Smok.37

The specific fluid systems addressed in this study include an air–water system (\( C = 0 \% \)), three copy paper systems with mass fraction concentrations (consistencies) of \( C = 0.5, 1, \) or 1.5\%, and one old newspaper system with a mass fraction of \( C = 1 \% \). Bubble diameter distributions are obtained at two column locations, the upper column region contains \( H = 15 \text{--} 40 \text{ cm} \), while the lower column region contains \( H = 115 \text{--} 140 \text{ cm} \). The superficial fluid velocity is fixed at one of two values \((v_l = 1 \text{ or } 2 \text{ cm/s})\), and the superficial gas velocity is fixed at one of three values \((v_g = 1, 2, \text{ or } 4 \text{ cm/s})\) for each test.

**Table 1. System Properties**

<table>
<thead>
<tr>
<th>system</th>
<th>air–water (AW)</th>
<th>copy paper (CP)</th>
<th>old newspaper (ONP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface tension (dyn/cm)</td>
<td>68</td>
<td>64</td>
<td>53</td>
</tr>
<tr>
<td>average fiber length (mm)</td>
<td>2.0</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>ash content (%)</td>
<td>6.6</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

**Results**

**Air–Water \( C = 0 \% \).** Representative radiographs of the air–water system (\( C = 0 \% \)) at each column height and superficial gas velocity are shown in Figure 2 for \( v_l = 1 \text{ cm/s} \). The \( 20 \times 25 \text{ cm} \) X-ray film is oriented such that the long dimension is in the flow direction. The film extended beyond the column width by 5 cm on each side, and these regions have been digitally removed to increase clarity. The reproduced and reduced radiographs do have some loss of detail, particularly with respect to the smallest bubbles, but are provided here for qualitative observations and are representative of the originals. All observations and measurements presented below are based on the original radiographs.

Figure 2 reveals that all conditions show many "small" bubbles and a few "large" bubbles (the dark regions represent bubbles). Large bubbles are defined in this study to correspond to \( d_b > 10 \text{ mm} \), in which wall effects will dominate the bubble size and shape.38

![Figure 2. Radiographs at \( C = 0 \% \) and \( v_l = 1 \text{ cm/s} \) for various superficial gas velocities and column heights.](image)

When \( d_b \leq 10 \text{ mm} \), the bubbles are termed "small". Others have also differentiated between large and small bubbles in bubble columns.13,14,39–42 For example, De Swart et al.13 also used \( d_b = 10 \text{ mm} \) as the demarcation between large and small bubbles.

The large bubbles oscillate in a serpentine pattern as they rise through the bubble column, creating turbulent vortices. As the superficial gas velocity increases, the size and rise velocity of the large bubbles increase, increasing the column turbulence. Backmixing is also observed at each superficial gas velocity and column height, and is confined to the sides of the column, outside the serpentine flow path. Small bubbles in these regions are observed to periodically travel down the column, but they eventually migrate into the main rise region and ascend with the other bubbles. This flow pattern has been observed by others in two-dimensional semibatch bubble columns43–48 and has been identified by Tzeng et al.43 as vortical flow. For a fixed column height, the radiographs shown in Figure 2 reveal a qualititative increase in the largest bubble size with increasing \( v_g \). For a fixed \( v_g \), there appears to be an increase in the number of large bubbles as the column height increases even though they make up a very small fraction of the total bubble population.

Multiple radiographs were taken at each test condition and analyzed using image analysis software to determine the bubble diameter distributions. Figure 3 reveals the bubble diameter number densities for \( C = \)
0% and \( v_l = 2 \text{ cm/s} \). The abscissa is read in the following manner: the region associated with “1” represents all bubbles with \( d_B \leq 1 \text{ mm} \); the next region represents bubbles with \( 1 \text{ mm} < d_B < 1.5 \text{ mm} \), etc. The last region on the abscissa (to the right of “10”) represents all large bubbles with \( d_B > 10 \text{ mm} \). The majority of the bubbles in Figure 3 fall in the size range with bubble diameters less than approximately 7 mm, well below the \( d_B = 10 \text{ mm} \) demarcation between large and small bubbles. Less than 2% of the various bubble populations are actually composed of large bubbles. The general shape of the bubble diameter number densities for all six conditions shown in Figure 3 are similar. The mean bubble diameters in each population, \( d_{B,m} \), are also similar.

Figure 3 also includes the Sauter mean diameter (\( S_B = \sum (n_{d_B} d_B^3) / \sum n_{d_B} d_B \)) for each bubble diameter population and has been used by other investigators to characterize bubble size in bubble columns.9,15,20,21,46–48 However, \( S_B \) assumes that all bubbles are spherical, which is clearly not the case for the large bubbles that are influenced by the column walls (e.g., see Figure 2 for \( C = 0% \) and \( v_l = 1 \text{ cm/s} \)). A more appropriate measure for the bubble sizes in this geometry is the maximum recorded equivalent bubble diameter, \( d_{B,max} \); this value generally increases with increasing \( v_l \) and column height.

The bubble diameter number densities in Figure 3 can be easily converted to cumulative number density distributions, as shown in Figure 4. A shift to slightly larger bubbles in the upper column region is observed when the data are plotted in this fashion, and it is attributed to bubble coalescence as they rise up the column. A similar, but smaller shift, is revealed with \( v_l = 1 \text{ cm/s} \) (not shown).

Figure 5 compares the cumulative bubble diameter distributions for \( C = 0% \), \( v_l = 1 \) or 2 cm/s, and \( H = 15–40 \text{ cm} \). All data follow similar trends up to approximately the 40th percentile, where the \( v_l = 1 \text{ cm/s} \) data shifts to slightly larger bubble diameters when compared to the \( v_l = 2 \text{ cm/s} \) data; however, this shift is not too significant. When \( H = 115–140 \text{ cm} \) (not shown), there is no effect of \( v_l \) for the range considered here. Hence, for the air–water system, there is only a small effect, if any, of \( v_l \) on bubble size, and this occurs only in the lower column region.

The cumulative bubble diameter distributions in Figure 5 appear to be qualitatively similar. To determine quantitative similarities/differences between the
Various cumulative number densities, a Kolmogorov–Smirnov two-sample statistical test was performed between each bubble diameter distribution in Figure 5. The test statistic for this test provides a measure of the maximum value of the absolute difference between two cumulative distribution functions. This value is then compared to a probability value which is a function of the population count of the two distributions used in the test. A positive Kolmogorov–Smirnov test is better suited for a discrete distribution, such as bubble diameter. A negative test is applicable to a continuous distribution, such as bubble diameter. A detailed description of this test is provided by Gibbons.49

The preceding bubble diameter distributions all follow similar trends, it may be possible to characterize them with standard distribution functions. Three such functions are shown in Figure 6a for $C = 0\%$, $v_B = 1 \text{ cm/s}$, $v_I = 2 \text{ cm/s}$, and $H = 115-140 \text{ cm}$. Because the bubble diameter is defined only for $d_B > 0$, the cumulative normal distribution is given by

$$\text{Cum}_N = \int_0^x \frac{1}{\sigma \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{y - \mu}{\sigma}\right)^2\right] \, dy$$

where $\mu$ and $\sigma$ are the mean and standard deviation of the bubble diameter. The cumulative log-normal distribution is given by

$$\text{Cum}_{LN} = \int_0^x \frac{1}{\sqrt{2\pi} \sigma_{LN}} \exp\left[-\frac{1}{2} \left(\ln(y) - \frac{\mu_{LN}}{\sigma_{LN}}\right)^2\right] \, dy$$

where $\mu_{LN}$ and $\sigma_{LN}$ are the mean and standard deviation of the natural logarithm of the bubble diameters. These values are not equivalent to $\mu$ and $\sigma$, but can be related by50

$$\mu_{LN} = \ln(\mu) - \frac{1}{2} \sigma_{LN}^2$$

$$\sigma_{LN}^2 = \ln\left[1 + \left(\frac{1}{\mu}\right)^2\right]$$

The cumulative gamma distribution is given by

$$\text{Cum}_G = \int_0^x \frac{1}{\beta \Gamma(\alpha)} y^{\alpha-1} e^{-\frac{y}{\beta}} \, dy$$

where $\Gamma(\alpha)$ is the gamma function and $\alpha$ and $\beta$ are parameters that characterize it and are related to $\mu$ and $\sigma$ by51

$$\mu = \alpha \beta$$

$$\sigma^2 = \alpha \beta^2$$

For the conditions in Figure 6a, the log-normal distribution provides the closest match to the experimental data. Similar observations have been provided by others.7,14,15,19,21,29 The few large bubbles in the population, corresponding to 1.9% of the total population of 761 bubbles and are as large as $d_{B,max} = 36 \text{ mm}$, prevent a better match to the data. If the large bubble population is filtered from the data set, a very close match between the small bubble population and a log-normal distribution is observed (Figure 6b). The gamma distribution also follows the data very well. Similar trends are observed with all other bubble diameter distributions obtained in this study.

**Effect of Cellulose Fiber Mass Fraction.** Three different fiber (copy paper) mass fractions are used to determine the effect of cellulose fiber on bubble diameter. When $C = 0\%$, the bubble column hydrodynamics are visually similar to those at $C = 0\%$. Large bubbles rise through the column in a serpentine pattern and backmixing is apparent. Increasing the superficial gas velocity produces a more energetic flow, increases the large bubble frequency, and large bubbles occupy a wider column region as they rise. The most significant differences between the $C = 0.5\%$ and $C = 0\%$ systems
are (i) an increase in large bubble size and (ii) an apparent decrease in the number of small bubbles. Using a semibatch two-dimensional bubble column with a system composed of air, paraffin oil, and glass particles, De Swart et al.\textsuperscript{13} also concluded that as the slurry concentration increases, the small bubble population decreases.

Figure 7 shows the bubble diameter number densities for a fiber mass fraction of $C = 0.5\%$ and $v_l = 2\, \text{cm/s}$. The number densities cover a wider range of bubble diameters than those observed at $C = 0\%$, but the number densities still follow similar trends with the majority of the bubble diameters in the $d_B = 1\text{--}8\, \text{mm}$ range. Slightly more bubbles than those observed at $C = 0\%$ are considered large ($d_B > 10\, \text{mm}$), with up to 2.5% of the bubble populations being categorized in this range. At this fiber mass fraction, the maximum recorded bubble diameter increases with increasing $v_g$ and $H$, and it is larger than that recorded at $C = 0\%$. Similar trends were identified in semibatch bubble columns by De Swart et al.\textsuperscript{13} and Luo et al.\textsuperscript{52} using glass and alumina particles, respectively.

The bubble diameter cumulative number density reveals the similarity in the $C = 0.5\%$ data (Figure 8). The superficial gas velocity has a small influence on the bubble diameter in the lower column region ($H = 1\text{--}40\, \text{cm}$), where increasing the superficial gas velocity shifts the bubble size to slightly larger diameters. This trend is not observed in the upper column region ($H = 115\text{--}140\, \text{cm}$), where the bubble diameter is unaffected by $v_g$ changes in the range $1\, \text{cm/s} \leq v_g \leq 4\, \text{cm/s}$.

Additionally, the bubble diameter distributions in the upper column region fall in the middle of those observed in the lower column region.

As indicated above, the presence of cellulose fibers does have an effect on the large bubbles; they are larger and occur at a slightly higher frequency at $C = 0.5\%$ than at $C = 0\%$. The large bubbles create turbulent mixing as they periodically ascend the column. The mixing energy maintains a fairly uniform fiber suspension, which prevents the coalescence of small bubbles and results in less small bubble diameter variation at $H = 115\text{--}140\, \text{cm}$ for the three superficial gas velocities considered in Figure 8. This is not observed in the lower column region because the very large bubbles that create the mixing energy form as they rise through the column, usually by the coalescence of bubbles with equivalent diameters on the order of $d_B = 10\text{--}20\, \text{mm}$. Hence, there is a turbulent mixing development length that extends beyond the lower column region and is created by the coalescence of large bubbles. At the same time, there is a suppression of bubble coalescence of the small bubbles because fibers prevent their collision between one another. Similar conclusions were observed by Lindsay et al.\textsuperscript{53} while investigating gas holdup in a cylindrical cocurrent bubble column filled with a $C = 1\%$ cellulose fiber slurry.

When the cellulose fiber (copy paper) mass fraction is increased to $C = 1\%$, the bubble column hydrodynamics are similar to those observed at $C = 0.5\%$; however, the serpentine flow pattern and backmixing are not as strong as observed at $C = 0.5\%$, resulting in a less energetic flow. The suppression of gas flow oscillations in fiber slurries have also been reported by Lindsay et al.\textsuperscript{53} in a cocurrent cylindrical bubble column and by Hendel\textsuperscript{54} in a semibatch rectangular bubble column. All $C = 1\%$ data follow similar trends to those observed at $C = 0.5\%$: (i) the majority of the bubbles are less than $d_B \approx 8\, \text{mm}$ in diameter; (ii) only a small percentage ($<4\%$) of the total population are large bubbles; (iii) the maximum bubble size increases with increasing $v_g$ and $H$. The most significant difference between the $C = 0.5\%$
and $C = 1\%$ data is that the large bubble population has increased from that observed at $C = 0.5\%$.

Figure 9 compares the $C = 1\%$ data at the two superficial liquid velocities of $v_l = 1$ or $2$ cm/s and $H = 115-140$ cm. The few large bubbles in each system provide mixing energy and the presence of fibers hinder small bubble coalescence; these factors result in similar bubble diameter distributions for each superficial liquid velocity.

At a fiber mass fraction of $C = 1.5\%$ and $v_l = 2$ cm/s, significant hydrodynamic changes occur when compared to lower fiber mass fraction systems. Although back-mixing is observed in the bubble column, the intensity is greatly reduced from that observed at the lower mass fractions. The fiber slurry also appears to be less turbulent and travels at a “slower pace” through the column. The serpentine rise pattern observed at the lower mass fractions is also more suppressed at $C = 1.5\%$ than at $C = 1\%$. Visually, the number of small bubbles decreased considerably and the frequency of large bubbles increased from that observed at the lower mass fractions.

Figure 10 displays the bubble diameter number densities for $C = 1.5\%$ and $v_l = 2$ cm/s. The most significant change from all previous number densities is the substantial increase in large bubble population (9—13%). Additionally, the total bubble population for each condition is considerably smaller than all previous tests and is due to the sever reduction in the small bubble population. The reduced bubble population produces more uncertainty in the bubble diameter distributions, but trends for this size range are qualitatively similar to those at lower mass fractions.

The effect of cellulose fiber (copy paper) mass fraction on the bubble diameter distribution is shown in Figure 11 for $v_g = 2$ cm/s, $v_l = 2$ cm/s, and $H = 15-40$ cm. The $C = 0\%$ system produces the smallest bubbles. Adding fibers produces a shift to slightly larger bubble diameter distributions, with $C = 0.5\%$ and $C = 1\%$ producing similar distributions. When $C = 1.5\%$, a significant change occurs and a shift to larger diameters is evident. The increase in large bubble population with increasing mass fraction is also very apparent. The same general trends in the lower column region are observed when $v_l = 1$ and 4 cm/s.

In the upper column region (Figure 12), a different trend is observed. The first approximately 50–70th
percentile of the C = 0% bubble population is larger than the bubbles in the fiber slurries. At C = 0%, the small bubbles are allowed to coalesce as they rise up the column in the air–water system. In contrast, the fibers prevent small bubble coalescence. Additionally, the C = 0.5–1.5% slurries have similar small bubble diameter distributions. It is clear that the number of large bubbles increases with increasing fiber mass fraction.

All bubble diameter distributions in this study were compared to one another using the Kolmogorov–Smirnov test. Some test conditions produce statistically similar bubble diameter distributions within a 95% confidence interval, others do not. The conditions with similar distributions and those with dissimilar distributions do not follow any specific trends, and conclusions from these comparisons cannot be drawn.

All bubble diameter distributions were also compared to normal, log-normal, and gamma distributions, similar to those in Figure 6. A log-normal distribution provides the best match to the data. Furthermore, all small bubble diameter data (d_b < 10 mm) are well-characterized by log-normal bubble diameter distributions, even the C = 1.5% conditions.

A summary of the effect fiber mass fraction has on the mean bubble diameter, Sauter mean diameter, and maximum recorded bubble diameter is presented in Figure 13 for \( v_g = 2 \text{ cm/s} \). In Figure 13a, the mean bubble diameter increases slightly with increasing fiber mass fraction up to C = 1%. At C = 1.5%, a large increase in \( d_{B,m} \) is recorded and is attributed to the significant hydrodynamic changes observed between C = 1 and 1.5%. The Sauter mean diameter may not be the best bubble diameter comparison because the large bubbles are typically nonspherical but is provided in Figure 13b for completeness; it generally increases with increasing fiber mass fraction. The general trends of increasing maximum recorded bubble diameter with increasing column height, superficial gas velocity, and fiber mass fraction are clearly shown in Figure 13c. Similar slurry concentration effects were observed by others in semibatch slurry bubble columns using high-density spherical particles, as well as low-density fibrous particles.

**Effect of Cellulose Fiber Type.** Two different cellulose fiber types, copy paper (CP) and old newspaper (ONP), at a mass fraction of C = 1% are used to determine if cellulose fiber type has an effect on bubble diameter. When ONP fiber is used in the bubble column at C = 1%, the hydrodynamics are visually similar to those observed in a CP system at C = 1%. If the bubble size distributions are compared between the two fiber types, the general bubble distribution shapes are similar, but ONP has a smaller large bubble population, a mean bubble diameter that decreases with column height, and a bubble diameter distribution that has shifted to slightly smaller values.

The latter trend is apparent in Figure 14, where the air–water system (C = 0%, AW), the copy paper system at C = 1% (CP), and the old newspaper system at C = 1% (ONP) are presented for \( v_g = 1 \text{ cm/s} \) and \( v_l = 2 \text{ cm/s} \). In the lower column region, there are no significant differences in the bubble diameter distributions between the three flow systems. In the upper column region, the AW bubble diameter distribution shifts to larger values. As previously discussed, this is attributed to bubble coalescence as the bubbles rise up the column. The CP and ONP fibers prevent the coalescence of small bubbles and yield a larger percentage of small bubbles in the upper column region. The ONP system also produces slightly smaller bubbles than the CP system in the upper column region. Since these are natural systems, it is hypothesized that the differences are due to residual contaminants found in the ONP system that are not found in the CP system. The ONP system...
produces smaller bubbles that are more stable than those in the CP system due to the added contaminants from the ONP, and the mixing caused by the rising large bubbles accentuates this effect, producing the results in Figure 14. Comparable results are revealed at \( v_g = 2 \) and \( 4 \) cm/s. A semibatch two-dimensional bubble column also produced similar results.\(^{30}\)

It is also possible that the differences in fiber length between the ONP and CP systems could influence the bubble diameter. However, using a semibatch rectangular bubble column, Heindel and Omberg\(^{55}\) concluded that synthetic (rayon) fiber length had a negligible effect on bubble size. Therefore, the fiber length effects in this study are assumed to be negligible for the given fiber lengths.

**Conclusions**

Flash X-ray radiography has been used to record bubble size in an opaque cocurrent air–water–fiber slurry. Results were presented for a range of fiber mass fractions (0 ≤ C ≤ 1.5%), a range of superficial gas velocities (1 ≤ \( v_g \) ≤ 4 cm/s), two superficial liquid velocities (\( v_l = 1 \) or 2 cm/s), and two column heights (H = 15–40 or 115–140 cm). The bubble diameters were divided into two size classes, small bubbles with \( d_B < 10 \) mm and large bubbles with \( d_B > 10 \) mm. All bubble diameter distributions were characterized by log-normal distributions. In general, the large bubble size and population increased with increasing column height, superficial gas velocity, and fiber mass fraction. The addition of fibers modified the cocurrent bubble column hydrodynamics, suppressed mixing, and promoted large bubble formation and growth. At the same time, the cocurrent flow of the fiber slurry hindered small bubble coalescence.

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**Nomenclature**

- \( AW \) = air–water
- \( C \) = fiber mass concentration
- \( CP \) = copy paper
- \( Cum_G \) = cumulative gamma distribution
- \( Cum_N \) = cumulative normal distribution
- \( Cum_LN \) = cumulative log-normal distribution
- \( d_B \) = bubble diameter
- \( d_{B,m} \) = mean bubble diameter
- \( d_{B,max} \) = maximum recorded bubble diameter
- \( H \) = column height
- \( n \) = number of bubbles with diameter \( d_B \)
- \( ONP \) = old newspaper
- \( Pop \) = bubble population
- \( S_B \) = Sauter mean diameter
- \( v_g \) = superficial gas velocity
- \( v_l \) = superficial liquid velocity
- \( y \) = dummy variable
- \( \alpha \) = gamma function parameter
- \( \beta \) = gamma function parameter
- \( \Gamma(x) \) = gamma function
- \( \mu \) = mean of the bubble diameter
- \( \mu_{LN} \) = mean of the natural logarithm of the bubble diameter
- \( \sigma \) = standard deviation of the bubble diameter
- \( \sigma_{LN} \) = standard deviation of the natural logarithm of the bubble diameter

**Literature Cited**


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