A review of gas flows in fiber suspensions

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ABSTRACT: This paper provides a review of gas flows in fiber suspensions. It describes general gas flow characteristics in fiber suspensions by summarizing fundamental research in this area. It also reviews applications of gas flows in paper recycling, pulping and bleaching, and papermaking unit operations.
Application: This paper helps mills appreciate the effects of air entrainment in their operations. An extensive reference listis provided to point the reader to more information.

Gas flows in fiber suspensions are found in all aspects of the pulp and paper industry, from paper recycling to pulping and bleaching to papermaking. Sometimes mills add gas intentionally for a specific purpose, as in flotation deinking or bleaching with gaseous chemicals, or gas is entrained unintentionally with undesirable results, as in washing and paper forming. Gas flows in fiber suspensions are very complex and have lead some investigators (e.g., [1, 2]) to conclude that gas flows in fiber suspensions require further study.

GAS FLOW FUNDAMENTALS IN FIBER SUSPENSIONS

Cellulose fiber suspensions are complex because the fibers have a density close to that of water and they can form flocs at fiber mass fractions as low as C = 0.3%, and continuous fiber networks when C $\gtrsim$ 1% [3]. When gas is introduced into a fiber suspension, the resulting flow is even more complicated because fiber network formation and flocculation can trap bubbles, preventing their rise to the surface. Individual bubbles must either bypass the flocs or coalesce with other bubbles to form a resultant bubble with a sufficient buoyant force to break through the fiber network [4]. If the fiber mass fraction is too high, preferential bubble rise paths may form in the fiber suspension where locally high fiber mass fraction regions (i.e., high floc concentrations) prevent bubble ascension, and most bubbles are diverted to rise in locally low mass fraction regions. This process is typically referred to as channeling. Ajersch and Pelton [5] observed that when a channel forms, a large bubble will rise quickly through the fiber suspension and many small bubbles subsequently follow in the channel. Hence, some regions will not be exposed to gas, which makes channeling detrimental to any process where uniform gas dispersions are desired for optimal performance.

Various gas flow characteristics are important to quantify multiphase systems; these include the local and average volumetric gas fraction (termed *gas holdup* or *void fraction*), gas flow regime, bubble size, bubble rise velocity, etc. Overall, gas holdup can be determined by noting the suspension level before and after gas introduction, but local gas holdup values, as well as other gas flow characteristics, are difficult to quantify in fiber suspensions. The literature describes general methods to record various gas flow characteristics in simple

multiphase flows [6-9]. These methods typically require optical access (e.g., high speed photography or particle image velocimetry) or invasive probes (e.g., hot-wire anemometry). Gas-liquid-fiber flows typically prevent optical access, and invasive probes provide regions for fiber stapling and/or flocculation, making traditional experimental techniques severely limited. Thus, noninvasive measurement techniques are almost a requirement for detailed quantification of gas-liquid-fiber flows.

Gas holdup

Walmsley initially quantified gas holdup in fiber suspensions, defined as the volumetric gas fraction (ε), using semi-batch cylindrical bubble columns with rectangular and circular cross-sections [10]. In this case, semi-batch means a gas stream is continuously bubbled through a fixed fiber suspension volume. He reported gas holdup values in a fiber system consisting of clove oil or water and fibers from bleached kraft pine, bleach kraft eucalypt, or recycled yellow pages. Gas holdup was recorded by observing the fiber suspension expansion when air was introduced into a fixed suspension volume. The gas holdup in these systems decreased when $C > 0.6\%$. Walmsley concluded that the decrease in gas holdup implied an increase in bubble coalescence and/or channeling, which lead to a reduction in the overall air-liquid interfacial area.

Went et al. [11] completed a similar study and observed the gas holdup was reduced from that recorded in an air-water system even with $C = 0.2\%$, and the difference increased as fiber mass fraction increased. When $C \geq 1\%$, the gas holdup remained constant for a given gas flow rate; this was attributed to fibers agglomerating into a large mat near the bottom of the column, lowering the effective fiber mass fraction in the upper column region. Reese et al. [12] also showed that the presence of cellulose fibers increased bubble coalescence and reduced the overall gas holdup compared to a gas-liquid system at the same gas flow rate. Furthermore, the larger bubbles increased the turbulence in the system and the degree of back-mixing in the column.

Schulz and Heindel [13] used a co-current bubble column (i.e., gas and liquid flowing in the same direction) to record gas holdup in a fiber suspension composed of unprinted old newspaper (ONP) at fiber mass fractions of $C = 0\%$, 0.8%, and 1.2%. The effect of fiber mass fraction on gas holdup was very complex (**Fig. 1**). At low liquid flow rates, gas holdup decreased with increasing fiber mass fraction. At higher liquid flow rates, gas holdup reached a maximum value when $C = 0.8\%$. They attributed this to a reduction in bubble coalescence and channeling at the higher liquid velocities. These trends were not always consistent and appeared to be influenced by liquid and gas flow rate and fiber mass fraction. However, in all conditions of this study, gas holdup was minimized when $C = 1.2\%$. The key conclusion from this study was that the presence of (ONP) fibers increased the gas holdup above that of a similar GL system at particular superficial gas and liquid velocities.

Lindsay et al. [1] measured gas holdup in a cylindrical semi-batch bubble column filled with ONP fibers at mass fractions of $C = 0\%$, 1%, and 2%, and in a co-current bubble column filled with either $C = 0$ or 1% ONP fiber suspensions. In the semi-batch bubble column, gas holdup values were less uniform and lower in the fiber systems, implying gas channeling and lower gas residency time in the suspension. In the co-current bubble column, the $C = 1\%$ fiber suspension had a higher gas holdup than that recorded for the water system, and the gas holdup increased when the superficial liquid velocity exceeded the superficial gas velocity.

Recent results by Su and Heindel [14] have shown that gas holdup in Rayon fiber systems can be described by the Zuber-Findlay drift-flux model [15]. They also determined

that increasing fiber length reduced gas holdup when $C \leq 1.4\%$ for all other conditions fixed. Fiber length had no influence on gas holdup when $C > 1.4\%$.

Flow regime

Two general flow regimes are commonly identified when describing gas flows confined in large diameter (i.e., $D \gtrsim 15$ cm) bubble columns. In the homogeneous or bubbly flow regime, gas bubbles are typically small and uniform in size, and rise in a homogeneous dispersion through a continuous liquid phase with minor interactions between bubbles. The heterogeneous or churn-turbulent flow regime is characterized by a heterogeneous flow of small bubbles and rather large bubbles that form by the coalescence of small and/or large bubbles. Heterogeneous flow is typically preceded by homogeneous flow as the gas flow rate is increased if the flow conditions are appropriate. The transition from homogeneous to heterogeneous flow has been further characterized as vortical flow in two-dimensional bubble columns [16] and vortical-spiral flow in three-dimensional bubble columns [17]. Ruzicka et al. [18] have also identified purely heterogeneous flow to correspond to those conditions in which homogeneous flow is not recorded at any gas flow rate.

Using unprinted copy paper fiber mass fractions from $0 \leq C \leq 5\%$, Heindel [19] investigated various gas flow regimes in a two-dimensional semi-batch bubble column using flash x-ray radiography to visualize the gas flows. For a fixed gas flow rate (**Fig. 2**), the flow regime changed from vortical to churn-turbulent to surge churn-turbulent, and finally to discrete channel flow as C increased from 0 to 5%. Using a similar bubble column, Heindel and Monefeldt [20, 21] have shown that for ONP fiber suspensions, the transition from homogeneous to heterogeneous flow occurred at lower superficial gas velocities as the fiber mass fraction increased. Reese et al. [12] also concluded that the hydrodynamic behavior of gas flows in fiber suspensions deviated from the behavior of a simple gas-liquid system, even at fiber mass fractions as low as $C = 0.1\%$.

Su and Heindel [14] used the Zuber-Findlay drift-flux model to determine flow regime from gas holdup measurements in air-water-Rayon fiber suspensions. Homogeneous, transitional, and heterogeneous flow conditions were observed at low mass fractions, but when $C \geq 0.6\%$, purely heterogeneous flow was observed (**Fig. 3**). Although longer fiber lengths reduced gas holdup, fiber length did not affect transition and purely heterogeneous flow was recorded between $C = 0.4\%$ and $C = 0.6\%$ for Rayon fiber lengths ranging from 3-12 mm.

All of the preceding flow regime studies involved two- and three-dimensional semi-batch bubble columns with relatively low fiber consistencies. Bennington [22] has completed work in which a fixed gas volume is mixed with a medium consistency fiber suspension in a high shear mixer. He identified six different flow or mixing regimes: (i) Couette-like, (ii) partial inward radial, (iii) outward radial, (iv) pulsing, (v) cellular, and (vi) flooding. **Figure 4** schematically represents these different flow regimes. The specific flow regime was a function of fiber mass fraction and gas holdup, with test conditions ranging $6\% \leq C \leq 14\%$ and $0 \leq \varepsilon \leq 0.2$, respectively. Of the six different flow regimes, only the outward radial and cellular flow regimes maintained fiber suspension motion throughout the containment vessel. Bennington identified the cellular flow pattern as the preferred flow regime because gas was more uniformly distributed in that regime than in the outward radial regime. Additionally, a gas volume limit can be reached beyond which mixing quality suffers.

Bubble size

Bubble size is a very important gas flow characteristic when investigating multiphase flows. For example, in the pulp and paper industry, effective bleaching with gaseous chemicals requires small bubbles that are uniform in size and homogeneously distributed throughout the system to maximize the mass transfer surface area and ensure bleaching uniformity. In flotation deinking, a bubble size distribution of relatively small bubbles is preferred to provide a range of bubble sizes with which various contaminant sizes can interact to form bubble-particle aggregates. Measuring bubble size distributions in gas-liquid-fiber systems, however, has been challenging.

Hunold et al. [23] measured bubble diameter in dilute fiber systems with $C \leq 0.5\%$ 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 fiber slurries have also been obtained by Ajersch et al. [24] 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 of the flow cell.

Reese et al. [12] used particle image velocimetry (PIV) 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. 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.

Heindel [25] 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 Garner [26] with cellulose fiber mass fractions as high as 1.5%. In that study, gas bubbles were divided into two categories, large and small, with a demarcation bubble diameter of $d_B = 12$ mm. 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 (**Fig. 5a**). It was further shown that the small bubble diameter distribution was independent of fiber mass fraction and well-characterized by a single lognormal bubble diameter distribution (**Fig. 5b**). This work was extended using three different cellulose fiber types and similar results were observed [27].

Heindel [28] reported bubble size in a two-dimensional co-current bubble column filled with various cellulose fiber types. The recorded bubble diameters were divided into two classes, small bubbles with $d_B \leq 10$ mm and large bubbles with $d_B > 10$ mm. All bubble diameter distributions were characterized by lognormal 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 co-current bubble column hydrodynamics, suppressed mixing, and promoted large bubble formation and growth. At the same time, the co-current flow of the fiber slurry hindered small bubble coalescence.

GAS FLOW APPLICATIONS IN FIBER SUSPENSIONS

In the pulp and paper industry, gas is intentionally injected into a fiber suspension during various paper recycling and pulping and bleaching operations. Gas may also be unintentionally entrained during other fiber processing operations or may be retained through poor deaeration processes. In any case, Wang et al. [29] state it is relatively easy to maintain an entrained air content of approximately $\varepsilon = 4\%$ in a $C = 1\%$ fiber suspension. In contrast, this air would readily escape from water. Gas in fiber suspensions, introduced either intentionally or unintentionally, can cause several problems in pulp and paper processing. **Table I** summarizes many of the problems associated with gas in fiber suspensions. This section will summarize gas flow effects relevant to paper recycling, pulping and bleaching, and papermaking.

Increases the effective volume of the process stream, reducing equipment capacity
Reduces the washing efficiency
Reduces the stock and filtrate densities, influencing consistency measurements
Floats stock in tanks and chests, influencing consistency control
Reduces the drainage efficiency
Enhances pump cavitation, resulting in pump damage
Reduces the mixing efficiency
Reduces delignification
Forms foam
Creates pinholes in the sheet
Lowers sheet strength, smoothness, and bulk density
Causes poor formation and runnability
Causes hydrodynamic and pressure pulse variations
Enhances flocculation
Creates sites for pitch, dirt, and other deposits
Increases microbial activity
Increases the number of sheet breaks

I: Pulp and paper mill problems related to gas flows in fiber suspensions [30-35].

Paper recycling

Gas flows in fiber suspensions common to paper recycling can be found in flotation deinking and direct-contact steam heating operations. In flotation deinking, gas (typically air) is injected into a dilute suspension of recycled fiber and contaminants, mixed to form bubble-contaminant particle aggregates, and then allowed to float to the surface where the contaminants are skimmed away. Gas holdup and bubble size are important parameters in this process. A higher gas holdup generally implies an increase in the interfacial area between

the gas and liquid and/or an increase in the gas residency time, both of which lead to higher separation rates [1].

Dessureault et al. [36] state that optimum flotation conditions are obtained at the highest gas holdup at which homogeneous flow is observed. However, heterogeneous flow is more typical of gas flows in fiber suspensions, even at very low gas flow rates [11, 12, 14, 19]. Janse et al. [37] argue that most studies do not use industrial-type fiber suspensions, which typically have process chemistry (i.e., surfactants) added to the suspension; these added chemicals have a significant influence on the bubble size and other gas flow characteristics. They concluded that the combination of surfactants and spargers with a small porosity generate very small bubbles in fiber suspensions. As a result, superficial velocities typically fall below 3 cm/s for optimum performance while homogeneous flow conditions are observed.

There are many different types of flotation deinking cells in operation [38, 39] Dessureault et al. [36] provide a summary of the benefits of countercurrent column flotation, in which the gas and fiber suspension flow in opposite directions. **Figure 6** shows a schematic of this cell. They concluded that the brightness gain and ink removal efficiency in a single stage of countercurrent column flotation were similar or better than other multistage flotation systems.

Finch and co-workers [37, 40, 41] also used column flotation to complete particle removal studies in a gas-liquid-fiber system with countercurrent operation. Gas holdup increased with increasing gas and accepts flow rate, and decreased with increasing fiber mass fraction [37, 40]. Flotation efficiency was also maximized at a particular gas flow rate [41]. The maximum removal efficiency at a given gas flow rate was attributed to the change in flow conditions from bubbly to churn-turbulent flow, and the optimal conditions were unique to specific applications [37].

Flotation can also promote fiber loss through entrainment of the pulp fibers into the foam [5, 42-45]. Fiber losses are generally higher in systems using small bubbles. Two entrainment regimes have been identified [5]:

1. In the absence of fiber flocculation, individual fibers and fines are transported to the foam and the consistency of the foam and bulk are similar.
2. In flocculated pulp, bubbles are diverted around the flocs and smaller fibers and fines are more easily transported to the foam and the foam consistency is less than the bulk.

Deng and Abazeri [43] also concluded that smaller bubbles enhanced fiber loss while an increase in froth height reduced fiber loss.

Flotation has been suggested as a means to fractionate fibers into different length ranges [44, 45]. Under appropriate operating conditions, longer fibers are typically found in the reject (froth) fraction of the flotation operation. However, according to Eckert et al. [45], there are some disadvantages associated with using flotation as a fiber fractionator, including long retention times implying large flotation cell volumes and low flow rates, a need for multiple flotation stages, and required large water volumes.

Paper recycling operations also use dissolved air flotation (DAF) to clarify white water. In this operation, pressurized white water is saturated with air and when the pressure is reduced, bubbles about 10-100 μm in diameter are produced *(46)*. According to Cyr et al. [46], two factors are important for successful DAF operation: average bubble size and

bubble size distribution, because bubbles that are too large are inefficient and bubbles that are too small are not very effective; and air quantity upon depressurization (i.e., gas holdup), because it is directly related to DAF power consumption. They determined that the DAF valve type, bubble volume concentration, saturation pressure, and surfactant and flocculant addition have a significant effect on DAF bubble size distribution and average bubble size.

Direct-contact steam heating is another process in paper recycling where gas flows in fiber suspensions are found. In this process, steam is added to the repulper to increase the temperature of the stock to decrease the repulping time, aid in fiber-contaminant separation, and improve contaminant removal in subsequent downstream operations. Gas (steam) holdup and bubble size are important to provide efficient, uniform heating to the stock.

Pulping and bleaching

Gaseous bleaching involves the addition of chlorine, oxygen, or ozone gas to react with the lignin in the pulp fibers. Two issues are of primary importance for effective gaseous bleaching [47, 48]: (i) the creation of a homogeneous mixture with sufficient interfacial area for mass transfer and (ii) the maintenance of a stable three-phase gas-liquid-fiber suspension for a suitable period. The importance of these issues is emphasized in low mass fraction gaseous bleaching systems by the discovery that combinations of ozone and chlorine dioxide act synergistically in the first stage of elemental chorine-free bleaching sequences [49]. Effective control of gas dispersion in medium mass fraction gaseous bleaching operations can also improve brightness and selectivity [50, 51].

Depending on the particular bleaching stage and process conditions, gas holdup during gaseous bleaching can range from 11% to 84% [47]. This gas volume can have a severe impact on the pumping capacity of the system, and once power input to the suspension is stopped, segregation of the gas phase may be observed [22]. The gas-liquid flow patterns inside a multiphase mixer are also known to affect gas-liquid mass transfer rates and mixer power consumption, and the geometry and operating conditions of the mixer have been shown to influence the resulting flow patterns [52, 53].

McDonough [54] states that there may be limitations to gas mixing in medium consistency pulps. As the gas content increases, bubble coalescence may occur, leading to channel formation and reduced bleaching reaction rates as the pulp progresses through the bleaching tower. Reese et al. also highlighted this conclusion [2]. Reeve et al. [55] also state that bubble coalescence and channeling can lead to severe localized corrosion problems in the bleaching tower.

If the quantity of gas, added or present in a fiber suspension, is too large, the gas can be held up in the mixer; this may severely compromise the ability to disperse energy in the suspension, significantly reducing mixing effectiveness and gas-liquid mass transfer during bleaching operations. Bennington et al. [48] measured gas-liquid mass transfer rates over a range of fiber suspension compositions and mixer operating conditions. They concluded that gas-liquid mass transfer rate is an order of magnitude smaller in a fiber suspension when compared to a water-only system at identical volumetric gas fractions and mixer power dissipation rates. Increasing the fiber concentration further reduced the gas-liquid mass transfer rate. If the gas content became too high in the fiber suspension, the ability of the mixer to disperse energy within the system was reduced, limiting the mixing effectiveness and further reducing gas-liquid mass transfer rates. Rewatkar and Bennington [53] extended this study and attributed the reduction in the gas-liquid mass transfer rates in the presence of fibers to a reduced turbulence level in the liquid phase.

Static mixing has also been shown as an effective means to uniformly mix a bleaching gas into a fiber suspension. Carlson [56] concluded that a bleaching gas can be injected through a porous injector right before a static mixer resulting in good bleaching between the gas and fiber suspension. To maintain a uniform gas dispersion prior to the bleaching tower, however, a suspension velocity of 1.5 m/s is required. If the suspension velocity is less than 1 m/s, gas bubble coalescence and stratified flow may result, which could lead to channeling in the bleaching tower.

Brownstock washing is also found throughout pulping operations and, as cited by Wang et al. [29], air content can influence washing efficiency in two ways. First, the driving force for effective washing is a good drum vacuum; this decreases as foam caused by excessive air builds up in the washer drop leg. Second, the presence of air bubbles will lower drainage rates through pulp pads. It was recently shown that stock air content can have a significant effect on drainage rates when bubble size is in a particular size range. Wang et al. [29] showed that bubbles with diameters greater than 10 mm, obtained in the presence of a defoamer and in the absence of black liquor, passed through the fiber pad formed on the washer drum, and these bubbles had little influence on the water flux through the washer. In contrast, when the bubbles were smaller than approximately 2 mm, they became trapped in the fiber pad and the liquor filtration flux could be reduced by as much as a factor of 100. Adding a defoamer diminished these detrimental effects, causing the small bubbles to coalesce and escape through the pad.

Papermaking

In papermaking, gas flows in fiber suspensions are an unwanted commodity but can be found in various amounts in most systems. Generally, the gas is air and it exists in three forms in papermaking fiber suspensions: free air, bound air, and dissolved air [33-35]. Free air can rise to the surface of the pulp suspension and form foam. It is typically composed of bubbles greater than 70-100 μm in diameter. Bound air consists of bubbles less than 70-100 μm in diameter that are attached to fibers. The combination of free and bound air comprise entrained air. Dissolved air is air in solution and causes no problems if it remains in solution. Entrained air, or other gasses, in fiber suspensions result from turbulent open channel flows, free falling stock or additives, or process equipment such as beaters, leaking pumps or pipes, washers, screens, or cleaners [30]. The relative proportion of entrained and dissolved air can change rapidly throughout the papermaking process and is influenced by stock temperature, pH, pressure, chemical content, process equipment, and equipment operation [35]. Matula and Kukkamaki [35] claim that the average size of a stabilized entrained air bubble is on the order of 100 microns and the total volume and quantity of these bubbles often exceeds that of the fibers in the suspension.

The actual amount of entrained air that can lead to noticeable papermaking problems depends on the type of paper machine, the paper grade, and the furnish. For example, Pietikainen [30] showed that an entrained air content of $\varepsilon = 0.12\%$-0.2% in a newsprint machine had many problems associated with the air content, while a fine-paper machine with an entrained air content of $\varepsilon = 0.1\%$-0.4% had no apparent effect on paper machine runnability. Actual measurement of entrained air in a mill setting can be challenging. These measurements are typically based on suspension density, ultrasonic velocity, or fiber compressibility and may not be automated [30, 33, 35, 57-59].

Proper mill operation can minimize air entrainment. However, it is relatively easy to sustain a dispersed air content of $\varepsilon = 4\%$ in a $C = 1\%$ fiber suspension [29], whereas in water, the air would readily escape. According to Hitzroth [32], Dosch et al. [60] claim that

when C ≲10%, the maximum gas content by volume corresponds to the fiber suspension consistency, however, Hitzroth [32] measured air entrainment and his results did not agree with those of Dosch et al.

Schulz and Scott [31] investigated air entrainment in a coated recycled boxboard mill. They measured air content at various places in the mill and determined entrained air was location dependent and there was no correlation among the various sample locations. They also recorded great variability in three headboxes at the same mill and hypothesized that the variations were characteristic of the furnish as well as the specific machine. They concluded that entrained air content is a gauge of machine cleanliness and performance–a well-running clean machine typically has less entrained air in the fiber suspension. Schulz and Scott [61] extended this work by focusing on controlled laboratory experiments. They concluded that three factors influence air content:

1. air entrainment characteristics of the fiber and other particles,
2. air entrainment characteristics of the suspending medium, including any dissolved components, and
3. air entrainment characteristics of the system's mechanical components.

Schulz and Scott [61] further developed a method to characterize the air-release properties of fiber suspensions. The air that will leave the system if sufficient time is provided describes the natural air-release characteristics of the fiber suspension, V_{nr}. The air that will not leave the system without assistance characterizes the natural tendency of the fiber to hold air, V_{ent}. If V_{ent} dominates, active methods such as defoamers, mechanical action, and deaerators are required to reduce the air content in the system. In contrast, if V_{nr} dominates, sufficient time must be provided to allow the air to escape.

Ajersch et al. [24] determined air content is very sensitive to pressure changes, and any change in pressure can induce air mass transport between dispersed and dissolved air content. This can have a significant effect on the air content in the approach flow system and headbox because local pressures in approach flow system can vary considerably. To remove air, defoamers have been shown to reduce or completely remove air bubbles in headboxes [62].

Defoamers are one approach to reducing unwanted air content in papermaking systems. Typically, defoamers are used in combination with mechanical deaerators. Various rotating devices (e.g., cleaners, screens, and pumps), can be used to remove some air. Deaerators are specifically designed to remove unwanted air by impinging a fiber suspension within a vacuum vessel to scrub the unwanted air out to the system [33].

Coating flows may also be found in papermaking operations. When air bubbles become entrained in a coating system, they can cause various quality problems on the coated product. Coating systems often include deaerators to remove unwanted air. Deaerators typically operate like a centrifugal cleaner, where the coating tangentially enters an inverted cone, rotates at high speed, and exits from the cone bottom. The high rotation speeds generate a high g-force, forcing the air to migrate toward the cone center for removal from the cone top. Although deaerators are used to remove air from coating flows, the effectiveness and efficiency of their operation are difficult to quantify.

FUTURE RESEARCH NEEDS

Gas flows in fiber suspensions form very complex slurry flows and have lead Lindsay et al. [1] and Reese et al. [2, 12] to conclude more research is needed to understand and quantify the gas flow characteristics of these flows. With additional research, improvements in pulp and paper processing can be realized.

Currently, no detailed data in actual flotation deinking systems are available of relevant parameters such as turbulence level and bubble size distribution [39]. These data are extremely difficult to obtain in actual systems, but are critical if successful models to this process are to be developed.

Janse et al. [37] have shown that more data are required under actual process conditions to better represent mill operations. Actual conditions typically include quasi-steady state or dynamic properties that must also be accurately tracked, leading Lindsay et al. [1] to conclude dynamic bubble size measurements are needed. Reese et al. [12] specifically identify bubble rise velocity, bubble shape, and bubble size as parameters that require further study in fiber suspension. The development of techniques mills can use to quantify gas flows on-site is critical to obtaining any of the listed parameters.

Developing a model of gas flows in fiber suspensions would assist in bubble size and gas holdup control strategies. Recent work showing that the Zuber-Findlay drift flux model can be used to describe gas flows in low consistency fiber suspensions is promising [14]. However, information at higher consistencies, and for different fiber types, are required for continued model development.

Further studies of gas flows relevant to medium consistency bleaching operations are required to improve delignification and reduce cellulose degradation. Information regarding the influence of bubble size, gas holdup, and flow regime on gas-liquid mass transfer could be used to control and optimize medium consistency bleaching. Bubble size control mechanisms also could be developed if optimal conditions can be identified.

Controlling bubble size would also benefit flotation deinking. Bubbles in fiber suspensions can be classified into two categories–small or large. For a fixed gas throughput, small bubbles are preferred in a flotation cell to increase the bubble surface area to which particles can attach. However, fibers promote large bubble formation [26, 28]. Therefore, it may be desirable to devise methods to modify the large bubbles in a fiber suspension to produce small bubbles.

Research focusing on coating deaerator effectiveness and efficiency is needed. For best results, researchers should use actual coating fluids and noninvasive measurement methods to measure gas holdup before and after the deaerator. It would also be beneficial to quantify the flow conditions inside the deaerator using coating fluids; this could be accomplished by X-ray imaging methods.

CONCLUSIONS

Gas flows in fiber suspensions are very complex and are found throughout pulp and paper processing. Various researchers have attempted to quantify selected gas flow characteristics in fiber suspensions. Some success has been achieved, but much more must be done to describe the complete picture.

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AUTHOR INSIGHTS

I completed this review article because of the importance of gas flows in fiber suspensions, and I could not find one place that summarized the latest research. This article will also help students and researcher who may be new to this area understand the complexities of gas flows in fiber suspensions.

This review summarizes the research of various investigators and will be used in my laboratory to introduce students to gas flows in fiber suspensions.

The most difficult part of this review article was deciding what to include and what not to include because gas flows and air entrainment are found throughout pulp and paper processing.

Mills may benefit from this review by having a greater appreciation for the effects of air entrainment in their operation. Additionally, a detailed reference list points the reader to more information if it is required.

Our next step in understanding gas flows in fiber suspensions is to develop noninvasive imaging techniques to better measure various gas flow parameters. We are currently constructing a facility to complete X-ray computed tomography and X-ray stereography imaging of large-scale (i.e., 32 cm in diameter and 4 m high) multiphase flows. This facility will be used to acquire gas flow characterization data that is currently unavailable. Our long-term goal is to improve various multiphase flow processes, including those found in the pulp and paper industry.

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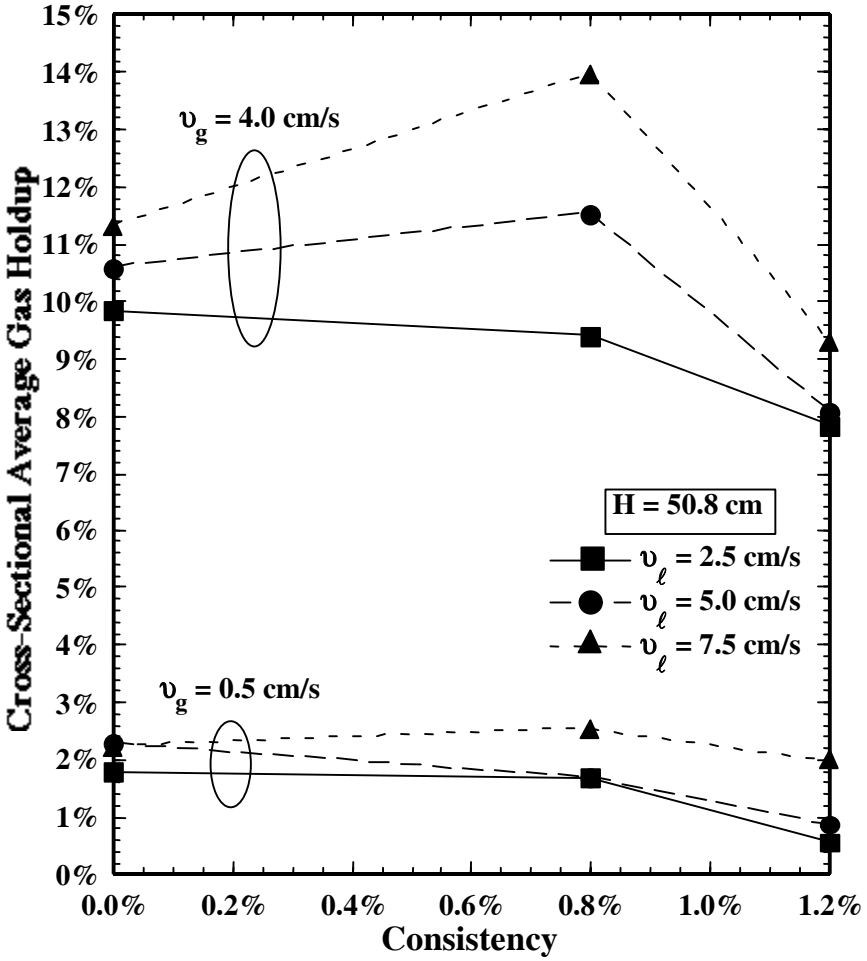
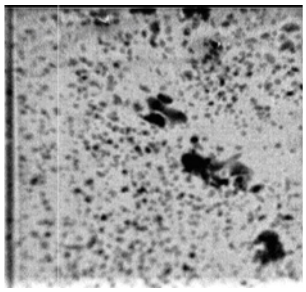
FIGURES



1. Cross-sectional average gas holdup as a function of ONP consistency at a column height of H = 50.8 cm (13).



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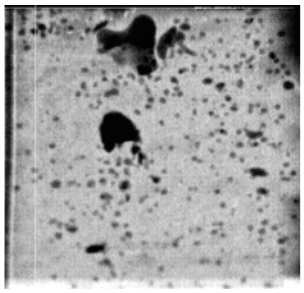

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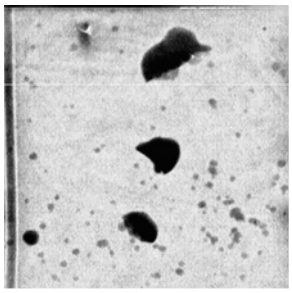

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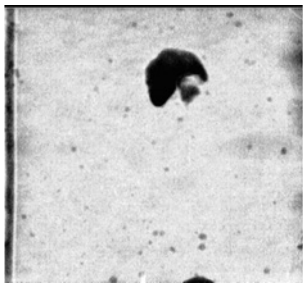

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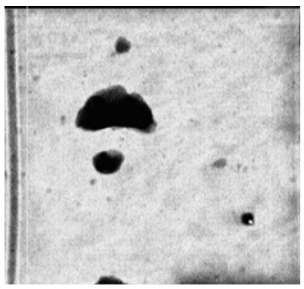

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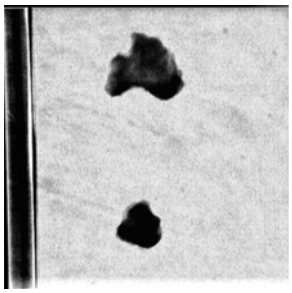

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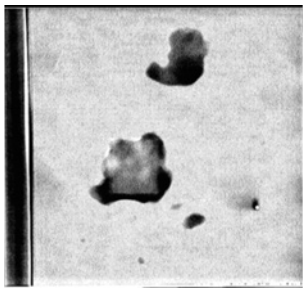

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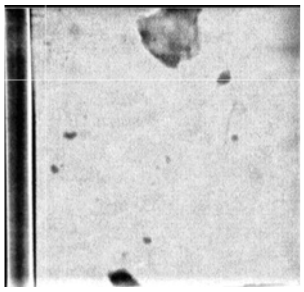

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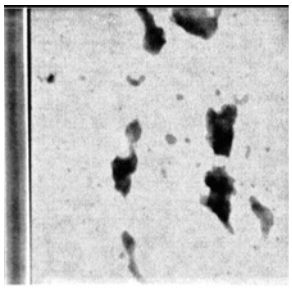

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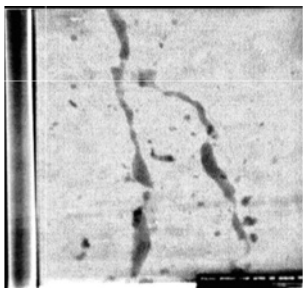

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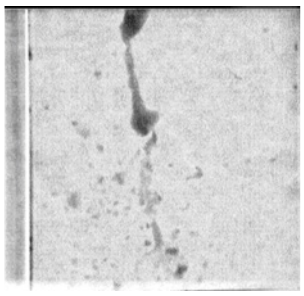

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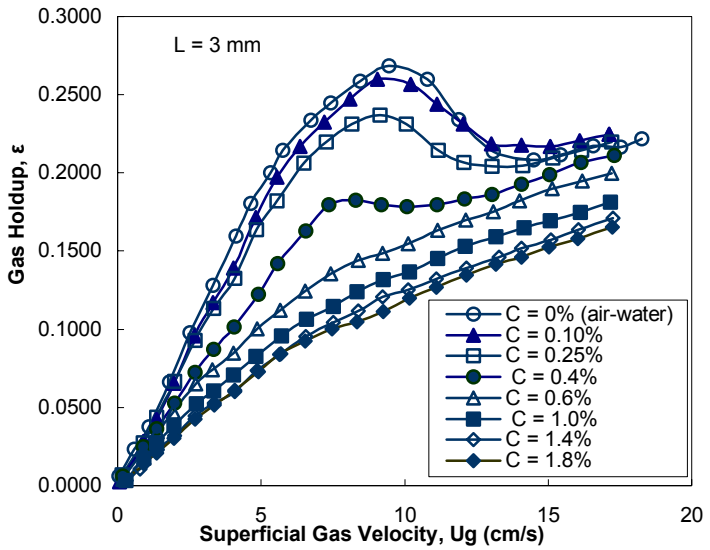
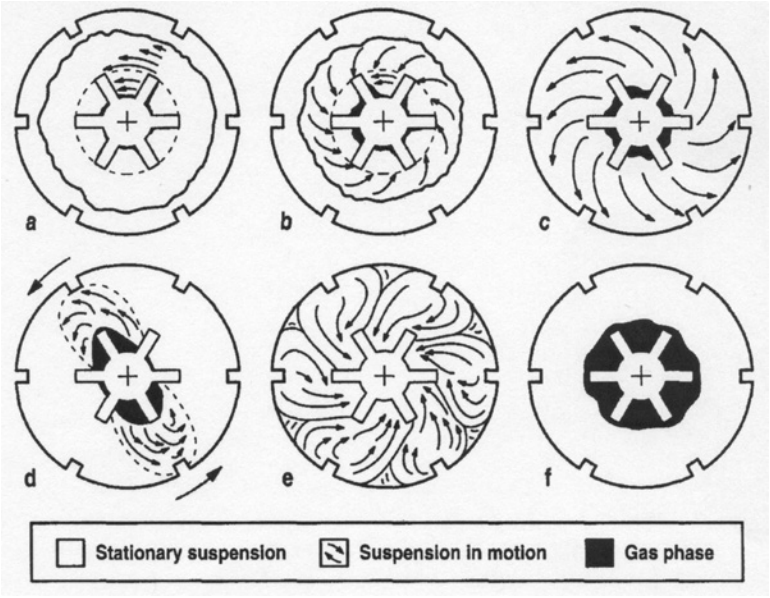
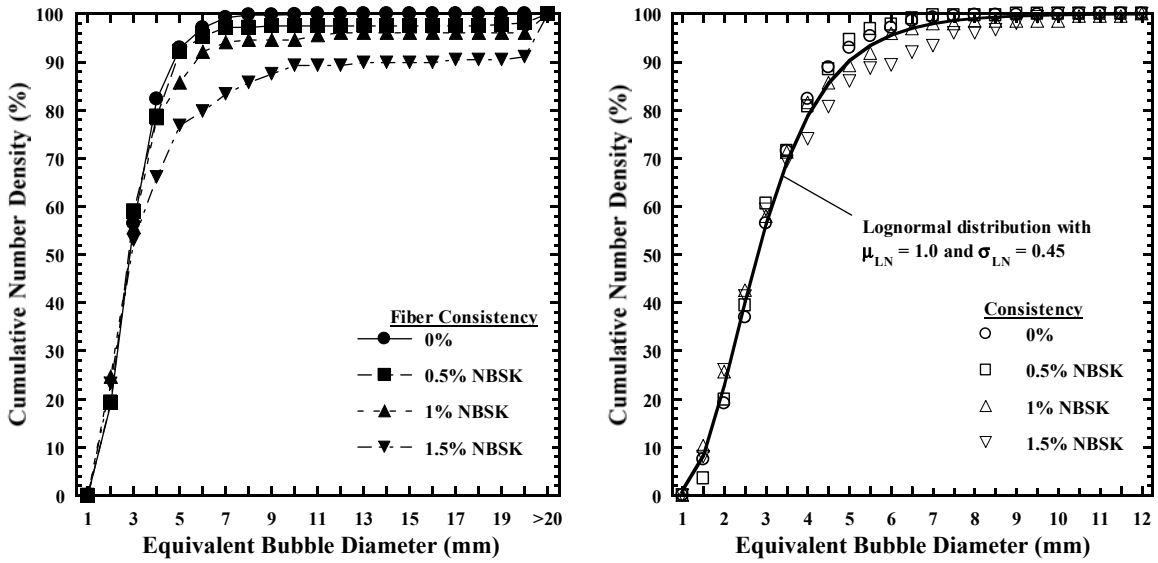
2. Radiographic images of gas flows in copy paper suspensions (19).



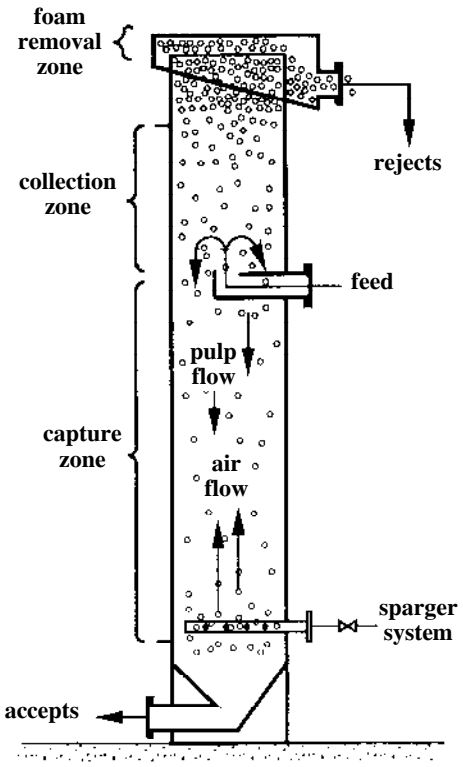
3. Gas holdup as a function of superficial gas velocity for various fiber mass fractions of 3 mm long Rayon fiber (14).



4. Gas flow regimes in a high shear mixer: (a) Couette-like, (b) partial inward radial, (c) outward radial, (d) pulsing, (e) cellular, and (f) flooding (22).



5. Bubble size distributions in Northern Bleached Softwood Kraft (NBSK) fiber suspensions: (a) all bubble size data and (b) all bubbles with d_B < 12 mm (26).



6. Schematic of a countercurrent flotation column.