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Effect of fiber type on gas holdup in a cocurrent air–water–fiber bubble column

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Abstract

An experimental investigation of the effect of fiber type on gas holdup in a cocurrent air–water–fiber bubble column is presented. Three types of cellulose fibers (i.e., hardwood, softwood, and bleached chemithermomechanical pulp (BCTMP)) and three different lengths of Rayon fibers are used in the investigation. The results indicate fiber type has a significant influence on the gas holdup in the air–water–fiber bubble column. Mechanisms by which fibers influence gas holdup in gas–liquid–fiber bubble columns are summarized and used to explain the experimental results. Fiber physical properties, including fiber length, coarseness, and flexibility are proposed to be the main factors responsible for the fiber type effects on gas holdup.

Keywords: Bubble column; Fiber suspension; Gas holdup; Hydrodynamics; Multiphase flow

1. Introduction

A bubble column is a contactor in which a discontinuous gas phase, in the form of bubbles, moves relative to a continuous phase, which can be a liquid or a suspension [1]. It is widely used to affect gas–liquid or gas–liquid–solid transport processes, which are found in many process industries. Recently, it was proposed to use a bubble column to affect flotation deinking [2–4], a key stage in paper recycling traditionally carried out in flotation cells involving gas–liquid–fiber flows. While some of the proposed flotation deinking columns are counter-current [2,4], cocurrent flows "offer the potential for increased interfacial area and higher gas holdup by reducing floc-induced coalescence" and should be "further exploited as a design principle in the future" [5]. In the pulp and paper industry, there are many other unit operations involving gas–liquid–fiber flows [6]. Furthermore, it has been shown that the addition of fibers into a process stream can provide advantages like drag reduction [7,8], fouling mitigation [9], and gas holdup enhancement [10,11], which may lead to new fiber applications. Thus, this study focus only on the effects of fiber type on gas holdup and other influences, like surface tension or surfactant usage, are minimized.

Gas holdup is defined as the volume fraction occupied by the gas phase in the total volume of the two or three-phase mixture. It is an important parameter in many gas–liquid or gas–liquid–solid transport processes. In the flotation deinking process, a higher gas holdup and smaller bubble size generally imply a larger interfacial area between the gas and liquid and/or a larger gas residence time, both of which lead to higher ink removal efficiency [5,12]. Bubble size distribution in gas–liquid–fiber flows and its variation with fiber mass fraction and fiber type have been investigated in semi-batch [13–15] and cocurrent bubble columns [16]. Gas holdup in gas–liquid–fiber systems has also been studied in both semi-batch [5,17–22] and cocurrent [5,10,11,23,24] bubble columns. Effects of superficial gas and liquid velocity, fiber mass fraction, and gas distribution method on gas holdup were studied in these investigations. However, only Walmsley [21] and Su and Heindel [19,22] reported fiber type effects on gas holdup in a semi-batch bubble column. A thorough investigation on fiber type effects on gas holdup in a cocurrent gas–liquid–fiber bubble column will add essential knowledge to the related industrial applications. It is acknowledged that the air–water–fiber flow studied here does not include the full

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complexities of the actual flotation deinking process, where (i) contaminants (e.g., ink particles and stickies) exist and (ii) flotation chemicals (e.g., proprietary surfactants) are usually added [3,25].

This paper focuses on fiber effects in gas–liquid–fiber slurries and extends the work of Tang and Heindel [23,24]. The effects of fiber type on gas holdup in a cocurrent air–water–fiber bubble column are investigated experimentally using three types of cellulose fibers (i.e., hardwood, softwood, and bleached chemithermomechanical pulp (BCTMP)) and Rayon fiber of three different lengths. The mechanisms behind the experimental results are discussed in detail.

2. Experimental methods

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

The spider sparger, shown in Fig. 2, has eight arms made of 12.7 mm diameter stainless steel tubes. Thirty-three 1.6 mm diameter holes are located on one side of each arm and distributed as shown in Fig. 2. The arms are soldered to the center cylinder of the sparger such that all the holes face the same direction. Air enters the spider sparger from the central cylinder and exits from the arm holes. The sparger is installed with the holes facing upward.

Three types of cellulose fibers and Rayon fiber of three lengths are used in this study. The cellulose fibers are hardwood, softwood, and bleached chemithermomechanical pulp (BCTMP). Their key physical properties are listed in Table 1. The Rayon fibers used in this study have a nominal length of 1, 3, or 6 mm. All Rayon fibers have a coarseness

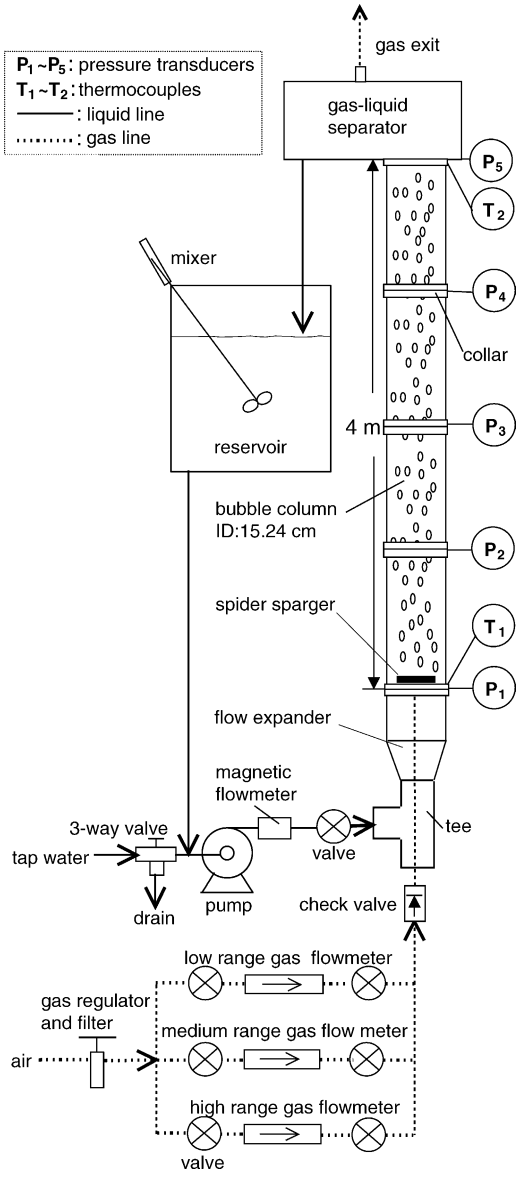

Fig. 1. Schematic of the cocurrent bubble column experimental facility.

of 50 mg/100 m, which corresponds to a fiber diameter of 20.6 μm.

All cellulose fibers are disintegrated from dry lap fiber sheets. The fiber sheets are originally torn into small pieces and then a specified mass of oven-dry fiber is weighed. It is then soaked in tap water for 24 h before the pieces of fiber sheet are disintegrated in a Black-Clawson laboratory hydropulper. The concentrated fiber suspension is then transferred to the reservoir and additional tap water is added to adjust the fiber mass fraction to a predetermined level. Rayon fibers are prepared slightly differently from the cellulose fibers. First, a specified mass of oven-dry fiber is weighed. Then the fiber is soaked in tap water for 24 h before it is repeatedly washed and soaked using tap water until the surface tension of the filtered water reaches a steady value of about 70 mN/m. This process removes a majority of the proprietary

Table 1
Cellulose fiber properties

Properties	Fiber type		
	Hardwood	Softwood	BCTMP
Wood species	Eucalyptus	65–75% Northern Black Spruce, 20–25% Jackpine, 5–10% Balsam Fir	Softwood (northern pine)
Length—PAFL (mm)	0.69	1.2	0.8
Length—LWAFL (mm)	0.78	2.31	1.91
Coarseness (mg/100 m)	6.9	13.08	29.5
Number of fibers per gram (millions)	21.4	6.37	4.25

PAFL: particle average fiber length, LWAFL: length weighted average fiber length.

additives attached to the fiber surface, which are gradually released into the fiber suspension and may affect the bubble column hydrodynamics. The washed Rayon fiber is then added into the reservoir and additional tap water is added to adjust the fiber mass fraction to a predetermined level.

During data acquisition, surface tension and pH of the water filtrate from the fiber suspensions are measured with a Sigma 703 digital tensiometer and a Milwaukee SM 802 pH/EC/TDS meter, respectively.

All experiments in this study are carried out under atmospheric pressure and ambient temperature. The superficial gas velocity range is $0 \leq U_g \leq 20$ cm/s, and the superficial liquid velocity range is $0 \leq U_l \leq 10$ cm/s. Fiber mass fraction C is defined as the ratio of the oven-dry fiber mass to the suspension mass. In this study, the fiber mass fraction range is $0 \leq C \leq 1.5\%$ for all fiber types except 6 mm Rayon fibers, which was $C \leq 0.4\%$ because of clogging in the 2.54 cm PVC pipe at fiber mass fractions higher than 0.4%.

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

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

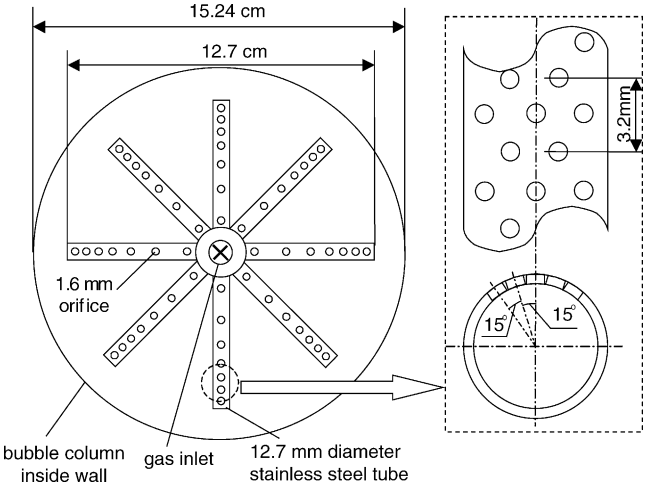

Fig. 2. Schematic of the spider sparger.

where $\Delta p_i = p_{L,i} - p_{H,i}$ is the pressure difference between the lower ($p_{L,i}$) and higher ($p_{H,i}$) ends of column section i ($i = 1$, 2, 3, 4); $\Delta p_{0,i}$ is the corresponding pressure difference when the column is filled only with the specified water–fiber suspension flowing at the same U_l. Eq. (1) accounts for the effects of wall shear stress but neglects the effect of liquid acceleration due to void changes that may influence gas holdup in cocurrent bubble columns [26–28]; however, these effects are estimated to be negligible for the conditions of this study [29]. The overall column gas holdup is defined as $\varepsilon = (\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/3$, the average gas holdup in the three lower sections. The gas holdup in the top section is not included in the overall gas holdup because of measurement error due to the void caused by large bubbles escaping the column top, which is significant during some experimental conditions [24].

Measurement uncertainties are estimated following the method provided by Figliola and Beasley [30] and details can be found in Tang [29]. The typical uncertainties associated with superficial velocities are ±2–4% for U_g and ±1.5–5% for U_l, respectively. The corresponding absolute gas holdup uncertainty is estimated to be $\Delta\varepsilon \approx \pm 0.005$–0.01.

3. Unique characteristics of fiber suspensions

3.1. Fiber physical properties

Cellulose fibers are reduced from wood (or other fibrous raw materials) via different pulping methods, including mechanical, chemical, or semichemical pulping processes, systematically rupturing the bonds within the wood structure [31]. A major difference between mechanically and chemically pulped fibers is that a mechanical fiber retains a majority of the lignin, while a chemical fiber is primarily lignin-free. The hardwood and softwood fiber in this study are chemically pulped, while the BCTMP fiber uses a combination of mechanical and chemical means to produce fiber.

Cellulose fibers from different sources have different morphological and mechanical properties [32,33]. For example, the average length of softwood fiber is up to two times longer than that of hardwood fiber [31]. The pulping, bleaching, and beating processes in the pulp and paper industry result in additional differences between fibers [34,35]. It has been

shown that cellulose fibers are more flexible when lignin is removed [36]. Rayon fibers are synthetically produced from regenerated cellulose and have much more uniform physical properties (e.g., fiber length and diameter). Other differences between Rayon and cellulose fibers include: (i) cellulose fibers have hollow centers called a "lumen", while Rayon fibers are flexible solid cylinders; (ii) cellulose fibers have locations along the fiber attributed to biological characteristics or mechanical damages resulting from processing operations (i.e., beating), producing "hinges" or "knees", while Rayon fibers usually lack such nonuniformity [37]; and (iii) cellulose fibers are usually subject to external fibrillation and micro-compressions in mechanical treatment and thus have surfaces morphologically different from those of smooth Rayon fiber surfaces [38]. These differences make cellulose fibers much more flexible than Rayon fibers, and the fiber–fiber contact mechanisms for cellulose fibers differ from those of Rayon.

3.2. Fiber suspension properties

A fiber can move in translation and rotation and sweep out a much larger volume than itself when suspended in a liquid, resulting in a large probability of contact with other fibers [39]. Furthermore, fibers are flexible and have a density close to that of water. Thus, fiber suspensions have a tendency to form regions where the fibers aggregate (i.e., flocculate) when a critical fiber mass fraction is reached. The critical fiber mass fraction is lower for a suspension made of longer, more flexible, and less coarse fibers; it is also a function of flow conditions [40–42].

When continuous fiber networks form, they possess a certain level of tensile and shear strengths [40]. One important parameter to characterize fiber network strength is yield stress, which is defined as the stress needed to cause relative motion in a fiber suspension. With a yield stress, a fiber suspension can be described by Bingham plastic models [43] or yield-pseudoplastic models [7,44–46]. The yield stress of a fiber suspension depends on fiber mass fraction, average fiber length, lignin content, fiber type, and amount of entrained gas [44,46–48].

The presence of fibers in a suspension can significantly suppress small-scale velocity fluctuations [36,49–51]. Norman et al. [49] suggested fibers damp turbulence intensity by supplying a force-bearing link between nearby fluid elements moving at different velocities, and thus suppressing the velocity difference. It was also reported that increasing the fiber mass fraction, length, and flexibility resulted in a higher reduction in the turbulence intensity [36,51].

3.3. Fiber suspension influences on gas holdup

When fibers are added to an air–water bubble column, bubble behavior will change due to the presence of fibers. Walmsley [21] illustrated four bubble motion modes in flocculated fiber suspensions. Ajersch and Pelton [52] identified four methods by which bubbles escaped from fiber networks. Based on detailed observations and available literature citations, six major mechanisms are proposed by which fibers influence gas holdup in a bubble column; they are summarized in Table 2 and details are provided below.

Table 2
Major mechanisms influencing gas holdup in a gas–liquid–fiber bubble column

Mechanism	Influence	Effect on gas holdup
I	Suppression of bubble coalescence	Increase
II	Increased bubble residence time	Increase
III	Enhanced bubble coalescence	Decrease
IV	Gas channeling	Decrease
V	Suppression of bubble breakup	Decrease
VI	Fluid property change	Increase

3.3.1. Mechanism I—suppression of bubble coalescence

Fibers can work as separation "walls" between bubbles, reduce their contact opportunity, and thus suppress bubble coalescence. This effect is particularly significant when bubbles are uniformly distributed in a fiber suspension at a high fiber mass fraction where continuous fiber networks form [24]. The ability of the fiber network to separate bubbles increases with increasing fiber mass fraction, but decreases with increasing bubble size and flow disturbance. Hence, in heterogeneous flows, characterized by large bubbles and turbulent mixing, Mechanism I has little influence on the large bubbles. However, small bubble coalescence can still be reduced by Mechanism I. This agrees with Heindel [16], who observed more small bubbles in a fiber suspension than an air–water system operating under the same condition. Bubble coalescence can still be reduced even when the fiber mass fraction is not high enough to form continuous fiber networks. Temporary fiber flocs usually form under this condition [40]. The fiber flocs remain between bubbles and reduce their collision probability. In a bubble column, Mechanism I usually results in an increase in gas holdup.

3.3.2. Mechanism II—increased bubble residence time

Fiber addition in a bubble column can increase bubble residence time. Fibers can form flocs or continuous fiber networks at high fiber mass fractions. The fiber networks can hinder bubble motion, especially when bubbles are small and the fiber suspension velocity is lower than the bubble rise velocity. Walmsley [21] observed that fiber-bubble collisions in a semi-batch bubble column slowed bubble rise velocity. Ajersch and Pelton [52] reported that a common phenomenon in flocculated fiber suspensions was that "air bubbles migrated upwards in a series of random discrete steps as these bubbles became repeatedly trapped and released from the pulp flocs." Reese et al. [18] recorded that the bubble rise velocity decreased with fiber mass fraction in a semi-batch air–water–fiber bubble column. They also reported that bubble rise velocity was higher near the column bottom, and the velocity difference between two fixed axial locations was

larger at higher fiber mass fractions. These observations were attributed to the resistance and tortuosity of bubble rise paths, both of which increased with increasing fiber mass fraction. The fiber network can also entrain small bubbles and make them move with the network [52]. This further enhances the bubble residence time because the residence time of a fiber suspension in a bubble column is typically longer than the gas phase residence time. One extreme example is that small bubbles stay in the fiber network even after the fiber suspension leaves the bubble column and is pumped back to the bubble column, causing a positive gas holdup even when no gas is released to the bubble column [5]. In semi-batch bubble columns or at low superficial liquid velocities in cocurrent bubble columns, Mechanism II causes a gas holdup increase in a bubble column, especially when small bubbles dominate the flow.

3.3.3. Mechanism III—enhanced bubble coalescence

When fibers form continuous networks, the fiber network can slow down and trap smaller bubbles, allowing coalescence with trailing bubbles [21,52]. This mechanism dominates the bubble behavior when three conditions are satisfied: (i) the diameter of the leading bubble is larger than the fiber spacing in the network; (ii) the leading bubble is not too large such that the buoyant force is not sufficient to break through the fiber network; and (iii) the bubble approaches the fiber network with a velocity higher than the local fiber suspension velocity. These three conditions hinder bubble rise and allow coalescence with trailing bubbles. One situation where these conditions are easily satisfied is in a bubble column aeration zone where gas is directly distributed into the column by a sparger [24] or perforated plate [18,19]. Condition (i) is satisfied when C is high enough to form a fiber network. For a suspension having a fiber mass fraction between 0.5% and 1.0%, most fiber spacing is on the order of 10 μm and it decreases with increasing fiber mass fraction [52]. Bubbles generated in the aeration zone are generally much larger, on the order of several millimeters [13,16]. Condition (ii) is satisfied when C is high enough such that the fiber network is sufficiently strong to hold a newly generated bubble. Condition (iii) is always satisfied in a semi-batch bubble column, and easily satisfied in the entrance region of a cocurrent bubble column, where bubbles are released at relatively high speed from the gas distributor. Mechanism III causes a significant decrease in gas holdup, which is more evident at higher fiber mass fractions.

3.3.4. Mechanism IV—gas channeling

When the fiber mass fraction is high, gas channeling occurs, significantly reducing the gas phase residence time. Channeling can occur at high fiber mass fractions (e.g., $C \approx 1.5\%$) when small bubbles are still found; in this case, a large bubble having a sufficient buoyancy force breaks through the fiber network and a non-static channel of low bubble rise resistance forms behind the bubble [53]. As the large bubble cleaves the fiber network, many small bubbles confined in the network near the path are released into the low fiber mass fraction channel, following behind the fast rising large bubble [21,52]. When the fiber suspension is very dense (e.g., $C \gtrsim 3.5\%$), a different type of channel forms. It becomes difficult for discrete bubbles to rise through the suspension and discrete semi-static gas channels are formed to allow the gas to pass. These channels remain active for periods of time ranging from a few seconds to a few minutes [53]. Both types of channels severely shorten the gas phase residence time. Mechanism IV results in a gas holdup decrease in a bubble column.

3.3.5. Mechanism V—suppression of bubble breakup

The presence of fibers in a bubble column can also suppress bubble breakup. It is very common that bubble breakup and coalescence occur simultaneously in a bubble column [54,55]. The bubble size distribution in the bubble column is determined by the dynamics of these two processes. It is widely accepted that only velocity fluctuations over a distance approximately equal to the bubble diameter are capable of causing bubble deformation and breakup while larger eddies merely transport the bubble [56,57]. Several studies have shown that the presence of fibers significantly changes velocity fluctuations in a turbulent flow field [36,49–51]. For most situations, turbulence intensity is reduced and turbulence damping occurs mainly at small length scales [50]. Thus, the addition of fibers can affect bubble shape and reduce bubble breakup. Mechanism V decreases gas holdup.

3.3.6. Mechanism VI—fluid property changes

Fiber addition can modify fluid properties, such as surface tension, when surface-active agents leach from the fiber into the liquid. Surfactants may also be added to the slurry for desired process characteristics (e.g., foam formation) [2,3,25]. Changes in the fluid properties can affect bubble size and bubble behavior. This can occur with certain types of cellulose [58] or synthetic [20] fibers. The surface-active agents usually cause a decrease in liquid surface tension, and produce a smaller, more stable bubble (i.e., one less prone to coalescence). Mechanism VI will increase gas holdup.

Mechanisms I–V are all functions of fiber suspension properties, which are in turn affected by fiber mass fraction and fiber physical properties. In a bubble column filled with a suspension made of longer, more flexible, and less coarse fibers, Mechanisms I–V tend to be stronger, providing other conditions (including fiber mass fraction, flow conditions, and lignin content, etc.) are similar. Since fiber physical properties vary with fiber type, gas holdup can change significantly in different fiber suspensions.

It is important to note that Mechanisms I–VI are not equal in their influence on gas holdup. Only a few of the mechanisms influence gas holdup for a given condition, and their importance changes with operating conditions. In most cases with semi-batch or cocurrent gas–liquid–fiber bubble columns, Mechanism III will dominate the flow; Mechanisms I, II, and V may also affect bubble behavior, but are less signif-

icant. However, if the fiber suspension has a vertical velocity larger than the bubble rise velocity of newly released bubbles, Mechanism III is negligible. Also, if the bubbles are distributed within a fiber suspension before they enter a bubble column, Mechanism I will dominate the bubble behavior in the lower region of the bubble column [5,10,11,24]. Finally, if surfactants are present, Mechanism VI may dominate the entire system [58].

4. Results

4.1. Fiber suspension surface tension and pH

There is no significant change in pH for the various operational conditions and fiber mass fractions addressed in this study. The pH for the different fiber types is in a range of 7.0–8.5, which is close to that of tap water.

The surface tension (σ) of softwood and BCTMP fiber suspensions as a function of fiber mass fraction are compared in Fig. 3, where the error bars show the standard deviation of multiple measurements. The surface tension of the softwood fiber suspensions does not significantly vary with fiber mass fraction, staying in a range of 63–69 mN/m. This is not far from that of tap water (~70 mN/m). Measurements in hardwood fiber suspensions at both low and high fiber mass fractions show similar surface tension values to that of softwood fiber. The surface tension of BCTMP fiber suspensions, however, decreases significantly with increasing fiber mass fraction in the range $0.05\% \leq C \leq 0.8\%$ and remains relative constant at about 50 mN/m when $1.0\% \leq C \leq 1.5\%$. This is reflected by a noticeable amount of foam observed in the reservoir and pump suction line. The BCTMP fiber used in this study was produced using sodium sulfite. Although the resulting pulp was washed and neutralized after beaching, it may still contain a small amount of lignosulfonates. Since lignosulfonate is water-soluble and a soap, it is believed that it was responsible for the foam that was produced with BCTMP fiber. The surface tension of the Rayon fiber suspensions is similar to that of water because it is the goal of the Rayon fiber processing procedure.

Since only BCTMP fiber suspension surface tension is significantly different from the other fibers, Mechanism VI will be considered in the following discussion only when BCTMP results are mentioned.

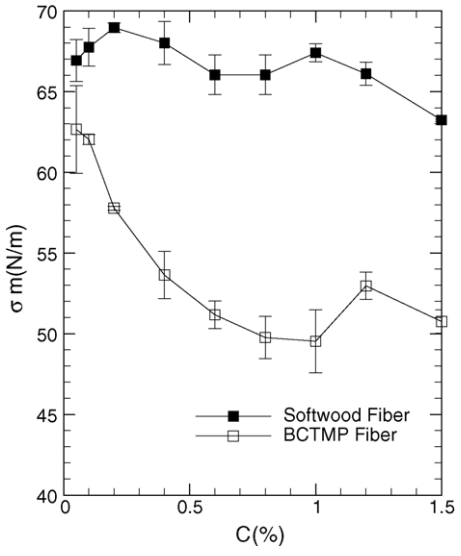

Fig. 3. Variation of fiber suspension surface tension with fiber mass fraction.

4.2. Gas holdup variation with fiber mass fraction

Typical gas holdup variation with fiber mass fraction in different fiber suspensions are presented in Fig. 4 for $U_l = 8$ cm/s and $U_g = 20$ cm/s. Similar data have also been taken at other superficial gas and liquid velocities and show similar trends. These data can be found in [29].

An overview of Fig. 4 and data in [29] indicate that the gas holdup for softwood and 6 mm Rayon fiber suspensions are very similar for all studied conditions. Gas holdup similarity between hardwood and 3 mm Rayon fiber suspensions is also observed. It is not fully understood why the gas holdup for the two pairs of fiber types are similar. However, it is possible that the effects of longer, stiffer Rayon fibers are offset by shorter, more flexible cellulose fibers. Additionally, cellulose fibers are hollow and have surface nonuniformities including "hinges" or "knees", as well as smaller diameters. Based on Fig. 4 and Tang [29], in the following, fiber type effects will be analyzed mainly between hardwood, softwood, BCTMP, and 1 mm Rayon fibers, assuming the effects of 3 mm (6 mm) Rayon fiber are similar to those of hardwood (softwood) fiber.

When a very small amount of fiber is added ($C = 0.05\%$) to the bubble column, gas holdup increases slightly when

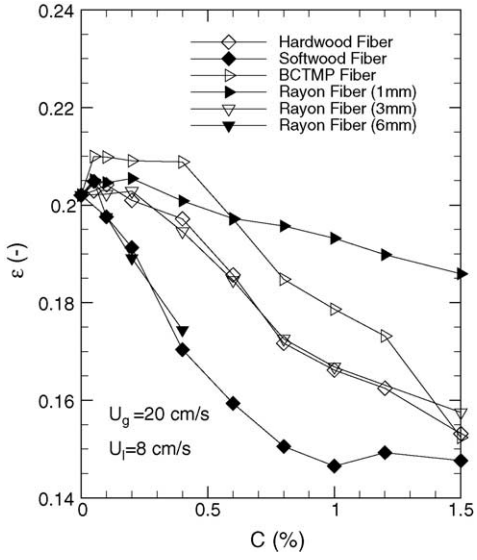

Fig. 4. Variation of overall average gas holdup with fiber mass fraction in different fiber suspensions when $U_g = 20$ cm/s and $U_l = 8$ cm/s.

compared to an air–water system ($C = 0\%$) operating under the same superficial gas and liquid velocities. This result was also observed by Walmsley [21]. The slight increase is attributed primarily to Mechanism I. The gas holdup increase in the BCTMP fiber suspension is larger, because Mechanism VI also contributes to the gas holdup increase, whereas it is not significant for the other fiber types.

As fiber mass fraction increases, gas holdup eventually decreases in a nonlinear fashion. For softwood fiber suspensions, gas holdup starts to decrease with increasing fiber mass fractions at $C = 0.1\%$. This is because in softwood fiber suspensions, fiber networks begin to form and Mechanisms III and V begin to contribute to the influence on gas holdup. For hardwood, 1 mm Rayon, and BCTMP fiber suspensions, the maximum gas holdup reached at $C = 0.05\%$ is relative unchanged with increasing fiber mass fraction until $C = 0.4\%$ (for hardwood and 1 mm Rayon fibers) or $C = 0.6\%$ (for BCTMP fibers), where gas holdup begins to decrease sharply with increasing fiber mass fraction. The gas holdup at first remains constant because negligible fiber flocculation is observed in this fiber mass fraction range for these fiber types and the effect of Mechanism III is negligible. Once the fiber mass fraction reaches a critical value where significant fiber networks form, Mechanism III dominates the flow and the gas holdup decreases with increasing C.

The fiber mass fraction at which the gas holdup starts to decrease with increasing C varies for different fiber types because fiber flocculation is affected by fiber physical properties including fiber length, coarseness, and flexibility. A suspension with longer or more flexible fibers begins to form flocs and fiber networks at lower fiber mass fractions and Mechanism III begins to dominate the flow. However, gas holdup in a BCTMP fiber suspension does not follow this trend because Mechanism VI dominates the flow until $C = 0.6\%$, when Mechanism III becomes significant.

When the gas holdup begins to decrease for all the fiber types except 1 mm Rayon fiber, the decline is very steep until $C \approx 0.8$–1.0%. The sharp decrease in gas holdup is attributed mainly to Mechanism III when $C \lesssim 0.8\%$. As fiber mass fraction increases, fiber network strength increases and the gas holdup decrease resulting from Mechanism III increases. The decline in gas holdup with increasing fiber mass fraction is steeper for softwood fibers than for hardwood or BCTMP fibers, while the slope for the latter two fiber types are similar (Fig. 4). This is attributed to fiber physical properties. Softwood fiber will cause more flocculation and increase fiber network strength more effectively than hardwood fiber at the same mass fraction because softwood fiber is much longer than hardwood fiber. Although BCTMP fiber is longer than hardwood fiber, it is less flexible because of the lignin content, which offsets the fiber length effect.

When $C \gtrsim 1.0\%$, the gas holdup decrease is less severe than when $C \lesssim 0.8\%$ (Fig. 4). For softwood fiber, gas holdup does not significantly change with increasing fiber mass fraction. The asymptotic reduction in gas holdup at the higher mass fractions is attributed to the following two reasons: (i) the amount of entrained gas in the fiber suspension increases with increasing fiber mass fraction and compensates for the decrease in gas holdup due to increasing fiber mass fraction; and (ii) enhanced bubble coalescence (Mechanism III) is not as significant because the fiber network strength is strong enough to make most newly generated bubbles coalesce in the aeration zone, especially for softwood fiber suspensions.

For 1 mm Rayon fibers, gas holdup decreases with increasing fiber mass fraction more gradually when $0.4 \leq C \leq 1.5\%$ (Fig. 4). No significant slope change is found because this Rayon fiber is short compared to the others, and Rayon is less flexible than cellulose fibers. Additionally, Rayon fiber surface morphology is smoother than cellulose, allowing the relatively short 1 mm Rayon to slide over each other as opposed to forming flocs in cellulose and longer Rayon fiber suspensions. Hence, the addition of 1 mm Rayon fibers into the suspension produces a much smaller enhancement of the fiber network strength when compared to the other fiber types.

4.3. Gas holdup variation with superficial gas velocity

Typical results on gas holdup variation with superficial gas velocity in different fiber suspensions at low ($C = 0.1\%$) and high ($C = 1.0\%$) fiber mass fractions and a fixed superficial liquid velocity ($U_l = 8$ cm/s) are shown in Fig. 5. Air–water data under similar operating conditions are also presented for reference. Additional data at other fiber mass fractions and superficial liquid velocities can be found in [29]. A general trend for all fiber types is that gas holdup increases with increasing superficial gas velocity without a local maximum. This is consistent with previous studies [11,18,21,24]. Hence, fiber type does not have an effect on the pattern of gas holdup trends with superficial gas velocity in this study. Other studies using semi-batch bubble columns [20,22] have concluded that fiber type and fiber length can influence gas holdup trends. The difference is primarily due to the gas distributors used in these studies.

Gas holdup in all fiber suspensions is compared in the range $0 \leq U_g \leq 20$ cm/s (Fig. 5a and b). Superficial gas velocity does not affect gas holdup trends among the different fiber suspensions. However, in Fig. 5a, the difference between the gas holdup in the BCTMP fiber suspension and that of the hardwood and 1 mm Rayon fiber suspensions is more significant at $U_g > 15$ cm/s than at $U_g < 15$ cm/s. Similarly, in Fig. 5b, the difference between the gas holdup in the BCTMP fiber suspension and that of the hardwood fiber suspension is more significant at $U_g > 8$ cm/s than at $U_g < 8$ cm/s. This is explained by the fact that at high superficial gas velocities (i.e., $U_g > 15$ cm/s at $C = 0.1\%$, or $U_g > 8$ cm/s at $C = 1.0\%$), a noticeable amount of foam is generated in the BCTMP suspension at the bubble column top and it is entrained into the bubble column due to backmixing, resulting in an additional increase in gas holdup. Backmixing is not significant at lower superficial gas velocities, so the gas holdup in the BCTMP

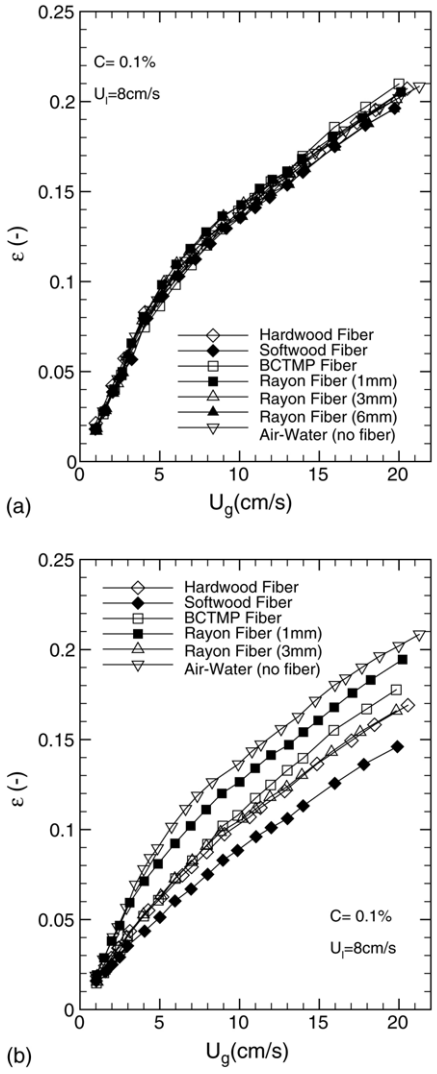

Fig. 5. Variation of overall average gas holdup with superficial gas velocity in different fiber suspensions when $U_l = 8$ cm/s: (a) $C = 0.1\%$; (b) $C = 1.0\%$.

fiber suspension is similar to other fiber suspensions. Foam in BCTMP suspensions begins to appear at a lower superficial gas velocity at $C = 1.0\%$ than $C = 0.1\%$, because there is more foam producing material (i.e., lignosulfonate) in the suspension when $C = 1.0\%$. Note that backmixing is observed for other fiber types under these conditions, but no foam is produced to enhance the gas holdup.

Extrapolating the gas holdup versus superficial gas velocity curves to $U_g = 0$ cm/s can be used to estimate if there is significant gas entrainment in the fiber suspension [5]. Hence, Fig. 5a indicates no air entrainment at $C = 0.1\%$ for all fiber types. However, a nonzero gas holdup ($\varepsilon \approx 0.005$) at $U_g = 0$ cm/s in Fig. 5b indicates a noticeable amount of gas entrained for BCTMP, hardwood, softwood, and 3 mm Rayon fibers when $C = 1.0\%$. Extrapolating the 1 mm Rayon fiber data to $U_g = 0$ yields $\varepsilon \approx 0$, implying no gas entrainment in this fiber suspension, even at $C = 1.0\%$.

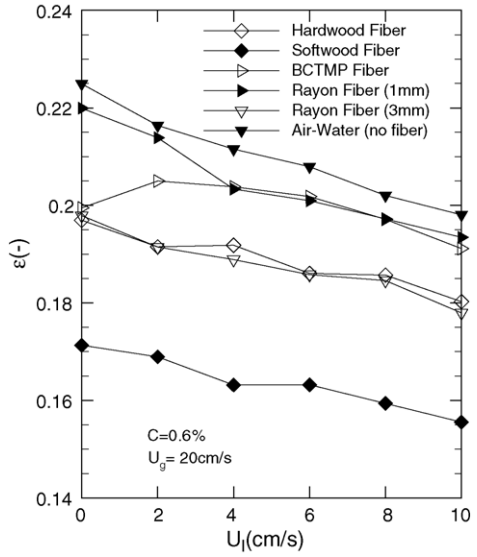

Fig. 6. Variation of gas holdup with superficial liquid velocity in different fiber suspensions when $U_g = 20$ cm/s and $C = 0.6\%$.

4.4. Gas holdup variation with superficial liquid velocity

Tang and Heindel [24] have shown that gas holdup decreases with increasing superficial liquid velocity due to a reduced bubble residence time, and the decrease is more significant in hardwood fiber suspensions when $C \lesssim 0.6\%$. This trend is generally true for all fiber types investigated in this study except BCTMP fiber (Fig. 6). As shown in Fig. 6 for $C = 0.6\%$ and $U_g = 20$ cm/s, gas holdup in the BCTMP fiber suspension increases when U_l is increased from 0 to 2 cm/s, reaching a maximum at $U_l = 2$ cm/s, and

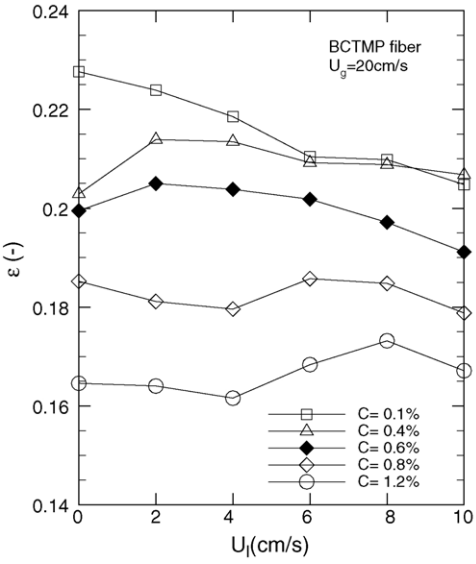

Fig. 7. Variation of gas holdup with superficial liquid velocity in BCTMP fiber suspension at different fiber mass fraction when $U_g = 20$ cm/s.

then decreases with increasing U_l. This general BCTMP trend is also found at other fiber mass fractions. However, as shown in Fig. 7, the superficial liquid velocity at which the gas holdup reaches a local maximum varies with fiber mass fraction. This behavior is the result of the foam formation in BCTMP fiber suspensions. Visual observations reveal foam forms inside the reservoir and at the top of the bubble column. The bubble column gas holdup increase from foam can be attributed to: (i) part of the foam formed in the reservoir is entrained in the fiber suspension and transferred into the bubble column by the pump when $U_l > 0$ cm/s; and (ii) the foam formed in the bubble column is entrained in the fiber suspension at the column top and transferred back to the bubble column due to backmixing. The complex interaction between these two effects, the superficial liquid velocity, and fiber mass fraction is not yet fully understood. More work is needed to fully understand why the gas holdup variation with superficial liquid velocity for BCTMP fiber suspensions deviates from the trends for other fiber suspensions.

5. Conclusions

An experimental program was completed to study the effect of fiber type on gas holdup in a cocurrent air–water–fiber bubble column. The results showed a significant fiber type influence. For all the investigated fiber types, gas holdup was a nonlinear function of fiber mass fraction. Generally, when $C \geq 0.4\%$, gas holdup decreased with increasing fiber mass fraction. For softwood and 6 mm Rayon fiber, this happened at a lower fiber mass fraction ($C = 0.1\%$). The rate at which gas holdup decreased with increasing C was largest for softwood and 6 mm Rayon fibers and smallest for 1 mm Rayon fibers. Gas holdup increased with increasing superficial gas velocity for all fiber types in this study. At given superficial gas and liquid velocities, the fiber type influence on gas holdup was also a complex function of fiber mass fraction. Foaming occurred in BCTMP fiber suspensions and affected the gas holdup in BCTMP fiber suspension significantly. Six mechanisms of fiber influences on gas holdup were summarized and used to explain the experimental results. It was proposed that fiber physical properties, including length, coarseness, and flexibility, are mainly responsible to the influences of fiber type on gas holdup.

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References

[1] Y.T. Shah, B.G. Kelkar, S.P. Godbole, W.D. Deckwer, Design parameters estimations for bubble column reactors, AIChE J. 28 (1982) 353–379.
[2] S. Dessureault, M.C. Barbe, M. Levesque, Column flotation: a new technology for deinking recycled pulp, in: TAPPI Proceedings of the 1995 Recycling Symposium, New Orleans, LA, 1995, pp. 251–255.
[3] C.A. Hardie, G.F. Leichtle, J.A. Watson, J.A. Finch, C.O. Gomez, Application of mineral processing techniques to the recycling of wastepaper, CIM Bull. 92 (1999) 131–137.
[4] C.O. Gomez, J.A. Watson, J.A. Finch, Recycled-paper deinking using column flotation, in: Proceedings of the Third Research Forum on Recycling, Vancouver, BC, Canada, 1994, pp. 41–44.
[5] J.D. Lindsay, S.M. Ghiaasiaan, S.I. Abdel-Khalik, Macroscopic flow structures in a bubbling paper pulp–water slurry, Ind. Eng. Chem. Res. 34 (1995) 3342–3354.
[6] T.J. Heindel, A review of gas flows in fiber suspensions, TAPPI J. 2 (11) (2003) 22.
[7] G.G. Duffy, A.L. Titchener, P.F.W. Lee, K. Moller, Mechanisms of flow of pulp suspensions in pipes, APPITA 29 (1976) 363–370.
[8] W.D. Mccomb, K.T.J. Chan, Drag reduction in fiber suspension, Nature 292 (1981) 520–522.
[9] J. Middis, S.T. Paul, H.M. Muller-Steinhagen, G.G. Duffy, Reduction of heat transfer fouling by the addition of wood pulp fibers, Heat Transfer Eng. 19 (1998) 36–44.
[10] T.H. Schulz, T.J. Heindel, A study of gas holdup in a cocurrent air/water/fiber system, TAPPI J. 83 (6) (2000) 58–59.
[11] T. Xie, S.M. Ghiaasiaan, S. Karrila, T. McDonough, Flow regimes and gas holdup in paper pulp–water–gas three-phase slurry flow, Chem. Eng. Sci. 58 (2003) 1417–1430.
[12] C.A. Hardie, C.O. Gomez, J.A. Finch, A venturi aerated column cell for deinking: effect of design and operating parameters, Prog. Pap. Recycl. 8 (4) (1999) 33–41.
[13] T.J. Heindel, Bubble size measurements in a quiescence fiber suspension, J. Pulp Pap. Sci. 25 (1999) 104–110.
[14] T.J. Heindel, A.E. Garner, The effect of fiber consistency on bubble size, Nord. Pulp Pap. Res. J. 14 (1999) 171–178.
[15] A.E. Garner, T.J. Heindel, The effect of fiber type on bubble size, J. Pulp Pap. Sci. 26 (2000) 266–269.
[16] T.J. Heindel, Bubble size in a cocurrent fiber slurry, Ind. Eng. Chem. Res. 41 (2002) 632–641.
[17] J. Went, M. Jamialahmadi, H. Muller-Steinhagen, Effect of wood pulp fibre concentration on gas hold-up in bubble columns, Chem.-Ing. Technol. 65 (1993) 306–308.
[18] J. Reese, P. Jiang, L.-S. Fan, Bubble characteristics in three-phase systems used for pulp and paper processing, Chem. Eng. Sci. 51 (1996) 2501–2510.
[19] X. Su, T.J. Heindel, Gas holdup in a fiber suspension, Can. J. Chem. Eng. 81 (2003) 412–418.
[20] X. Su, T.J. Heindel, Gas holdup behavior in Nylon fiber suspensions, Ind. Eng. Chem. Res. 43 (2004) 2256–2263.
[21] M.R.W. Walmsley, Air bubble motion in wood pulp fiber suspension, in: APPITA 46th Annual General Conference Proceedings, Launceston, Australia, 1992, pp. 509–515.
[22] X. Su, T.J. Heindel, Effect of gas distributor on gas holdup in fiber suspensions, in: Proceedings of the 2004 ASME Heat Transfer/Fluids Engineering Summer Conference, Charlotte, NC, 2004.
[23] C. Tang, T.J. Heindel, Gas holdup in a cocurrent air–water–fiber bubble column, in: Proceedings of the 2004 ASME Heat Transfer/Fluids Engineering Summer Conference, Charlotte, NC, 2004.
[24] C. Tang, T.J. Heindel, Gas–liquid–fiber flow in a cocurrent bubble column, AIChE J., 2005, in press.
[25] M.A. McCool, Flotation deinking, in: R.J. Spangenberg (Ed.), Secondary Fiber Recycling, TAPPI Press, Atlanta, GA, 1993, pp. 141–162.

[26] S.B. Kumar, M.P. Dudukovic, B.A. Toseland, Measurement techniques for local and global fluid dynamic quantities in two and three phase systems, in: J. Chaouki, F. Larachi, M.P. Dudukovic (Eds.), Non-Invasive Monitoring of Multiphase Flows, Elsevier, New York, 1997, pp. 1–45.
[27] J.H. Hills, The operation of a bubble column at high throughputs, Chem. Eng. J. 12 (1976) 89–99.
[28] J.C. Merchuk, Y. Stein, Local hold-up and liquid velocity in air-lift reactors, AIChE J. 27 (1981) 377–388.
[29] C. Tang, Hydrodynamics and gas holdup in a cocurrent air–water–fiber bubble column, Ph.D. Thesis, Iowa State University, Ames, IA, 2005.
[30] R.S. Figliola, D.E. Beasley, Theory and Design for Mechanical Measurement, 3rd ed., John Wiley & Sons Inc., New York, 2000.
[31] G.A. Smook, Handbook for Pulp and Paper Technologist, 2nd ed., Angus Wilde Publications Inc., Vancouver, BC, Canada, 1992.
[32] M.-S. Ilvessalo-Pfaffli, Fiber Altas: Identification of Papermaking Fibers, Springer-Verlag, Berlin, 1995.
[33] D.C. McIntosh, Fiber structure and properties, in: K.W. Britt (Ed.), Handbook of Pulp and Paper Technology, 2nd ed., van Nostrand Reinhold, New York, NY, 1970, pp. 37–46.
[34] A.M. Scallan, H.V. Green, The effect of pulping upon the dimensions of wood tracheids, Wood Fiber 7 (3) (1975) 226–233.
[35] L. Paavilainen, Conformability flexibility and collapsibility of sulfate pulp fibers, Pap. Puu 75 (1993) 689–702.
[36] O.L. Forgacs, A.A. Robertson, S.G. Mason, The hydrodynamic behaviour of paper making fibers, in: F. Bolam (Ed.), Transactions of the Symposium on Fundamentals of Papermaking Fibers, Cambridge, 1957, Technical Section of BP&BMA, Surrey, England, 1958, pp. 447–479.
[37] T.J. Stenuf, J.E. Unbehend, Hydrodynamics of fiber suspensions, in: N.P. Cheremisinoff (Ed.), Encyclopedia of Fluid Mechanics, vol. 5, Gulf Publ. Co., Huston, TX, 1986, pp. 291–308.
[38] R.S. Seth, W.D. Francis, C.P.J. Bennington, The effect of mechanical treatment during medium stock concentration fluidization on pulp properties, APPITA J. 46 (1993) 54–60.
[39] S.G. Mason, Fiber motions and flocculation, TAPPI J. 37 (1954) 494–501.
[40] R.J. Kerekes, R.M. Soszynski, P.A. Tam Doo, The flocculation of pulp fibers, in: V. Punton (Ed.), Transactions of the Eighth Fundamental Research Symposium on Papermaking Raw Materials, vol. 1, Oxford, September 1985, Mechanical Engineering Publications Limited, London, UK, 1985, pp. 265–310.
[41] R.J. Kerekes, C.J. Schell, Effects of fiber length and coarseness on pulp flocculation, TAPPI J. 78 (2) (1995) 133–139.
[42] A.A. Robertson, S.G. Mason, Flocculation in flowing pulp suspensions, Pulp Pap. Mag. Can. 55 (1954) 263–269.
[43] W.C. Chase, A.A. Donatelli, J.W. Walkinshaw, Effects of freeness and consistency on the viscosity of hardwood and softwood pulp suspensions, TAPPI J. 72 (5) (1989) 199–204.
[44] C.P.J. Bennington, R.J. Kerekes, J.R. Grace, The yield stress of fiber suspensions, Can. J. Chem. Eng. 68 (1990) 748–757.
[45] R.J. Kerekes, Characterizing fiber suspensions, in: Proceedings of the TAPPI 1996 Engineering Conference, vol. 1, Chicago, IL, 1996, pp. 21–28.
[46] C.P.J. Bennington, G. Azevedo, D.A. John, S.M. Birt, B.H. Wolgast, The yield stress of medium- and high-consistency mechanical pulp fiber suspensions at high gas contents, J. Pulp Pap. Sci. 21 (1995) J111–J118.
[47] T. Wikstrom, A. Rasmuson, Yield stress of pulp suspensions: the influence of fibre properties and processing conditions, Nord. Pulp Pap. Res. J. 13 (1998) 243–250.
[48] H.J. Youn, H.L. Lee, An experimental investigation of the effect of pulp types, mechanical treatments and crill contents on fiber network strength, Nord. Pulp Pap. Res. J. 17 (2002) 187–192.
[49] B.G. Norman, K. Moller, G.G. Duffy, Hydrodynamics of papermaking fibers in water suspension, in: Transactions of the Symposium on Fiber–Water Interaction in Papermaking, Oxford, British Paper and Board Industry Federation, London, UK, 1978, pp. 195–249.
[50] M. Steen, On turbulent structure in vertical pipe flow of fiber suspensions, Nord. Pulp Pap. Res. J. 4 (1989) 244–252.
[51] S.R. Andersson, A. Rasmuson, Flow measurements on a turbulent fiber suspension by laser Doppler anemometry, AIChE J. 46 (2000) 1106–1119.
[52] M. Ajersch, R. Pelton, The behavior of air bubbles in aqueous wood pulp suspensions, in: Proceedings of the Fifth Research Forum on Recycling, Ottawa, Ont., Canada, 1999, pp. 97–112.
[53] T.J. Heindel, Gas flow regime changes in a bubble column filled with a fiber suspension, Can. J. Chem. Eng. 78 (2000) 1017–1022.
[54] J.W.A. DeSwart, R.E. vanVliet, R. Krishna, Size, structure and dynamics of ”large” bubbles in a two-dimensional slurry bubble column, Chem. Eng. Sci. 51 (1996) 4619–4629.
[55] T. Otake, S. Tone, K. Nakao, Y. Mitsuhashi, Coalescence and breakup of bubbles in liquids, Chem. Eng. Sci. 32 (1977) 377–383.
[56] R. Clift, J.R. Grace, M.E. Weber, Bubbles, Drops and Particles, Academic Press, New York, NY, 1978.
[57] J.F. Walter, H.W. Blanch, Bubble break-up in gas–liquid bioreactors: break-up in turbulent flows, Chem. Eng. J. 32 (1986) B7–B17.
[58] P. Janse, C.O. Gomez, J.A. Finch, Effect of pulp fibers on gas holdup in a flotation column, Can. J. Chem. Eng. 77 (1999) 22–25.