

GENERAL RESEARCH

Gas Holdup Behavior in Nylon Fiber Suspensions

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The gas holdup behavior in a nylon fiber suspension with various fiber lengths ($L = 2, 3,$ and 6 mm) is investigated. Experiments are performed over a range of superficial gas velocities ($U_g \leq 18$ cm/s) and a range of fiber mass fractions ($0 \leq C \leq 1.8\%$) in a 15.24-cm-diameter semibatch bubble column. Day-to-day variations in the gas holdup create difficulties in interpreting the effect of the fiber mass fraction. These variations are attributed primarily to nylon fiber surface additives leaching into the suspension water and loss of hydrophobicity in a prolonged water environment. As an alternative, the gas holdup in rayon fiber suspensions is highly reproducible.

Introduction

Gas flows in fiber suspensions occur in many unit operations in pulp and paper manufacture, from paper recycling to pulping and bleaching to papermaking. Unlike conventional solids used in gas–liquid–solid slurry systems, which are typically spherical, or slightly irregular, fiber is flexible and has a large aspect ratio, leading to fiber deformation and orientation as additional suspension characteristics.^{1,2} In addition, mechanical contacts result in fiber–fiber interaction, which makes the effective viscosity of the fiber suspension increase significantly with fiber addition.³ Fiber flocculation is an additional phenomenon in semiconcentrated and concentrated fiber suspensions and is closely related to fiber shape, stiffness, mass fraction, aspect ratio, and interfiber friction.¹ This can lead to a different suspension rheology for different fiber types and mass fractions, which in turn leads to different gas flow behavior in the resulting fiber suspension. Therefore, rheological characteristics of fiber suspensions are very complex and result in very complex gas flow behavior in a fiber suspension; the latter is the focus of this paper.

Gas holdup behaviors in natural fiber suspensions have been investigated. Walmsley⁴ used two- and three-dimensional semibatch bubble columns and fiber suspensions derived from bleached kraft pine (BKP), bleach kraft eucalyptus (BKE), and recycled yellow paper (RYP). It was recorded that in BKP and BKE the gas holdup increased above that of an air–water system when the fiber mass fraction (C) was small; when $C > 0.6\%$, the gas holdup decreased with increasing fiber mass fraction. However, no gas holdup enhancement was observed in RYP; instead, the gas holdup monotonically decreased with increasing fiber mass fraction. The gas holdup was not significantly affected by further fiber addition when $C > 2\%$. Went et al.⁵ observed that in a semibatch bubble column the gas holdup decreased with increasing fiber mass fraction, and when $C \geq 1\%$, the effect of fiber mass fraction leveled off; this was at-

tributed to fibers agglomerating in a large mat near the bottom of the column, lowering the effective fiber mass fraction in the upper column region. Lindsay et al.⁶ showed that in a semibatch bubble column the gas holdup is lower in a fiber system than in an air–water system because gas channeling results in a lower gas residency time. Similar observations were made by Reese et al.⁷

The gas holdup in a cocurrent fiber slurry bubble column has also been studied. Using unprinted old newspaper, Lindsay et al.⁶ observed that in a cocurrent bubble column the gas holdup is greater than that of the air–water system when $C = 1\%$. Extending this study, Schulz and Heindel⁸ recorded that at low liquid flow rates the gas holdup decreased with increasing fiber mass fraction; at high liquid flow rates, the presence of fibers increased the gas holdup above that of a similar gas–liquid system, and a maximum gas holdup was reached at $C = 0.8\%$. Recently, Xie et al.⁹ used kraft softwood pulp and applied γ -ray densitometry to measure the gas holdup and showed that the gas holdup reached a maximum value at $C = 1\%$ for most of the liquid flow rates in their study.

More recently, the gas holdup behavior in synthetic fiber (rayon) suspensions with various fiber lengths was studied by Su and Heindel¹⁰ in a semibatch bubble column. The gas holdup decreased with increasing fiber mass fraction when $C \leq 1.2\%$, and beyond this fiber mass fraction, fiber channeling and settling in the bottom of column produced a negligible change in the gas holdup. Increasing the fiber length tended to reduce the gas holdup when $C \leq 1.4\%$.

All of the previous studies used natural cellulose fiber or fiber (rayon fiber) derived from cellulose. The gas holdup was highly repeatable, which indicates that the properties of cellulose or cellulose-derived fiber suspensions are relatively stable. Some synthetic fibers, especially those derived by the polycondensation method, are prone to degradation,¹¹ which could modify the fiber suspension rheology and the resulting gas flow behavior. In this study, the gas holdup behaviors in fiber suspensions comprised of various lengths ($L = 2, 3,$ and 6 mm) of nylon fiber, a noncellulose fiber derived by the

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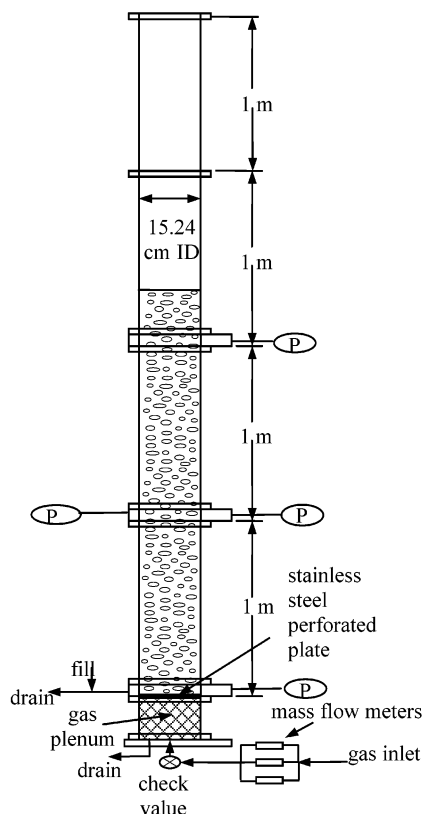


Figure 1. Experimental bubble column.

polycondensation method, are investigated over a range of fiber mass fractions ($C \leq 1.8\%$) and superficial gas velocities ($U_g \leq 18$ cm/s).

Experimental Procedures

The bubble-column experimental facility used in this study is schematically represented in Figure 1. The bubble column consists of four 1-m sections of 15.24-cm-i.d. cast acrylic, yielding a total column height of 4 m. Gas is injected at the base of the column through a stainless steel perforated plate, which is comprised of 130 1-mm-diameter holes to yield an open area of 0.57%. A gas plenum is located below the perforated plate and is filled with glass beads to promote uniform gas distribution into the test facility. Three mass flowmeters are used to measure the gas flow rate to encompass a low, medium, and high gas flow rate range, and a check valve prevents liquid backflow into the mass flowmeters. Four pressure transducers are installed along the column, one located at the column base, two at $H = 1$ m, and one at $H = 2$ m, where H is the column height from the perforated plate. The mass flowmeters and pressure transducers are interfaced to a data acquisition system.

The gas–liquid–fiber system is composed of air, water, and nylon fiber. Suspensions composed of three nominal nylon fiber lengths are investigated ($L = 2, 3,$ and 6 mm), and the fiber diameter is $27 \mu\text{m}$. Various fiber mass fractions ($0 \leq C \leq 1.8\%$) and superficial gas velocities ($U_g \leq 18$ cm/s) are investigated. The superficial liquid velocity in the study is held constant at zero.

The gas holdup (ϵ) is measured in the upper column section ($1 \leq H \leq 2$ m), where it is assumed that the bubble behavior is not influenced by the distributor region (near the column base). The gas holdup is

determined from the pressure drop. In a semibatch system, the frictional pressure drop is negligible, so the total pressure drop corresponds to the hydrostatic head; in this case,

$$\epsilon = 1 - \Delta P / \Delta P_0 \quad (1)$$

where ΔP is the pressure drop between any two pressure transducers with $U_g > 0$ and ΔP_0 is the corresponding pressure drop with $U_g = 0$. For the gas–liquid system, ΔP_0 equals that of the liquid hydrostatic head; for the gas–liquid–fiber system, ΔP_0 corresponds to that of the unaerated fiber slurry hydrostatic head.

Experiments are performed at specified fiber mass fractions (C), where the actual fiber mass (M_f) added to the system is determined from

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

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

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

and the dry nylon fiber density is $\rho_f = 1140$ kg/m³ and V is the volume of the fiber–water mixture.

Before an experiment is initiated, the dry fiber mass calculated from eq 2 is washed two to three times using tap water to remove any residual contaminants and soaked in tap water for 3–5 days to remove additives absorbed on the surface of the fiber. The soaked fiber is then added to a small container of water and mixed at low speed using an electronic mixer equipped with a propeller blade. The resulting mixture is then added to the bubble column that is partially filled with water. Additional water is added to fill the column to a height of 2.13 m (14 column diameters). All experiments are initiated with this slurry volume. The column is then operated at a high gas flow rate for approximately 35 min to ensure the slurry is well mixed throughout the column. The gas flow rate is then reduced to the lowest value of interest to begin data collection and then incremented sequentially for additional data points. Note that data are collected approximately 15 min after each gas flow rate adjustment. The gas used in all experiments is filtered compressed air.

Results and Discussion

Effect of Fiber Mass Fraction on Gas Holdup.

The effect of fiber mass fraction on gas holdup with $L = 6$ mm is shown in Figure 2. Note that these data were taken on the same day that the fiber was added to the bubble column. The gas flow characteristics of the air–water system for this experimental setup have been described in detail by Su and Heindel.¹⁰ In nylon fiber suspensions, the gas flow is in the purely heterogeneous regime for most fiber mass fractions (except $C = 0.05\%$). Even at $C = 0.05\%$ the gas holdup behavior deviates from that of the air–water system, and no local maximum gas holdup behavior is observed over the entire range of superficial gas velocities. Visual observations at $C = 0.05\%$ reveal that the flow conditions are not homogeneous and bubbles are not uniform in size, even when $U_g \leq 0.9$ cm/s. Under these conditions, two types of bubbles are observed: (i) relatively large ellipsoidal

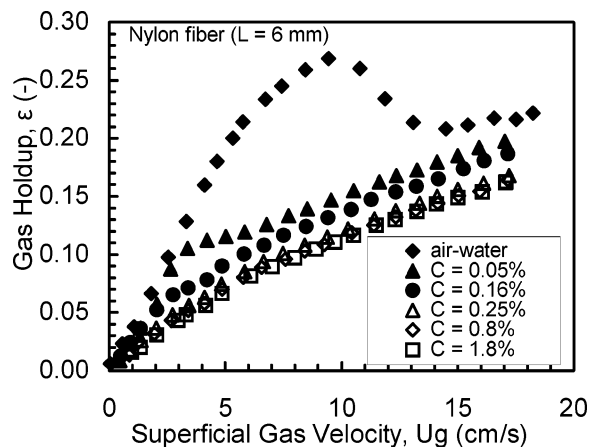


Figure 2. Gas holdup as a function of the superficial gas velocity for various nylon fiber mass fractions.

bubbles (~15 mm in diameter) and (ii) small spherical bubbles (~2 mm in diameter). At higher superficial gas velocities, large spherical-cap bubbles are also observed. Similar phenomena were observed by Philip et al.¹² in highly viscous liquids. They suggested two mechanisms to explain the appearance of small spherical bubbles: (i) bubble coalescence occurred near the gas distributor plate, and during the coalescence process, smaller bubbles are generated by the breakup of the trailing bubble; (ii) entrained small bubbles were generated by the breakup of a large bubble at the liquid surface. Mechanism (i) contributes to the small bubble appearance when the gas flow rate is low. When the gas flow rate is high, the accumulation of small bubbles is attributed to both mechanisms. The presence of small spherical bubbles in a nylon fiber suspension implies that even a small amount of nylon fiber leads to suspension behaviors similar to those of highly viscous liquids. Tse et al.¹³ give another explanation of small bubble formation in that small bubbles may be generated by the coalescence-mediated breakup of bubbles and state that this mechanism is very significant in systems that are coalescence-dominated. This mechanism could also contribute to the small bubbles observed in the heterogeneous gas flow regime found in the nylon fiber suspensions of this study.

Experimental observations reveal that nylon fibers tend to agglomerate with other fibers and bubbles. Visual observations made after shutting off the gas flow show that nylon fibers form flocs, which contain many small bubbles; these flocs float to the top of the column even though the fiber density is slightly greater than that of water. It is also observed that at very low superficial gas velocities a single small bubble may rise with several fibers attached to it.

From the data shown in Figure 2, it is seen that the gas holdup data taken on the first day that the fiber is added to the bubble column tend to decrease with increasing nylon fiber mass fraction. The decrease in the gas holdup is more pronounced at low fiber mass fractions ($C \leq 0.25\%$), and this effect diminishes when $C > 0.25\%$. These general fiber mass fraction trends qualitatively agree with those observed in rayon fiber systems;¹⁰ however, the influence of the fiber mass fraction occurs up to $C = 1.2\%$ in a rayon fiber suspension.

Similar trends are observed in nylon fiber systems with $L = 3$ mm when the fiber is soaked for 3–5 days before experiments are initiated. When fiber is soaked

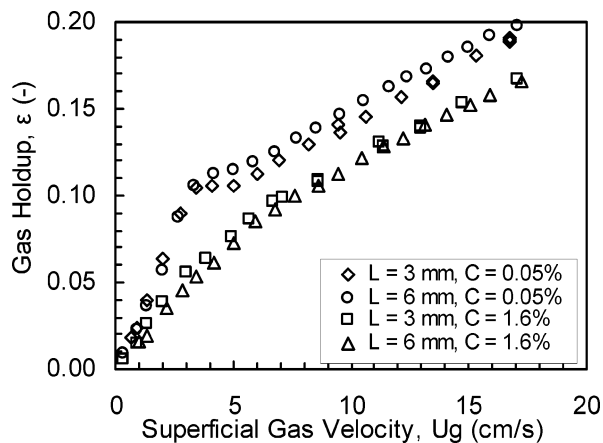


Figure 3. Effect of the nylon fiber length on gas holdup at various fiber mass fractions.

for 2 weeks before it is added to the bubble column, different behavior is recorded and will be discussed below.

Effect of Fiber Length on Gas Holdup. Figure 3 shows the effect of nylon fiber length on gas holdup, which reveals little influence. The gas holdup in shorter nylon fiber suspensions ($L = 3$ mm) is no different from that of longer fiber suspensions ($L = 6$ mm) at all fiber mass fractions including low ($C = 0.05\%$) and high ($C = 1.6\%$) fiber mass fractions. These observations contradict those of Su and Heindel,¹⁰ who found that the gas holdup decreased with increasing fiber length when $C \leq 1.4\%$ in rayon fiber suspensions. The negligible dependence of the gas holdup on the nylon fiber length may be because nylon fiber is stiff, leading to a small effect of the fiber aspect ratio on suspension rheology.

Comparison of Gas Holdup with Rayon Fiber Suspension. Figure 4 compares the gas holdup results in nylon and rayon fiber suspensions with $L = 6$ mm and various fiber mass fractions. At a low fiber mass fraction of $C = 0.16\%$, the gas holdup in the nylon fiber suspension is much lower than that in the rayon fiber suspension. Additionally, heterogeneous flow exists over the entire range of superficial gas velocities in the nylon suspension, while three flow regimes (homogeneous, transitional, and heterogeneous) exist in the rayon suspension. When $C = 0.8\%$, only purely heterogeneous flow is observed for both the nylon and rayon suspensions, but the gas holdup in the nylon suspension is lower than that of the rayon suspension. The gas holdup difference between nylon and rayon suspensions decreases with increasing fiber mass fraction, and at $C = 1.8\%$ (Figure 4c), there is a negligible difference between the two systems.

The hydrophobic nature of the nylon fiber surface is one possible mechanism to explain why the gas holdup in a nylon fiber suspension is much lower than that in a rayon fiber suspension at low fiber mass fractions. Many studies^{14–17} have been conducted on the effect of particle wettability on bubble behavior and gas holdup and point out that the gas holdup in a nonwetttable particle slurry is lower than that in a wetttable particle slurry. They claim that an important characteristic observed for nonwetttable particles is a high tendency for bubbles to attach to the particles, and the particles tend to form aggregates; this is consistent with the phenomena observed in the nylon fiber suspension of this study. In comparison, rayon fiber disperses uniformly and individual fibers can be clearly seen when

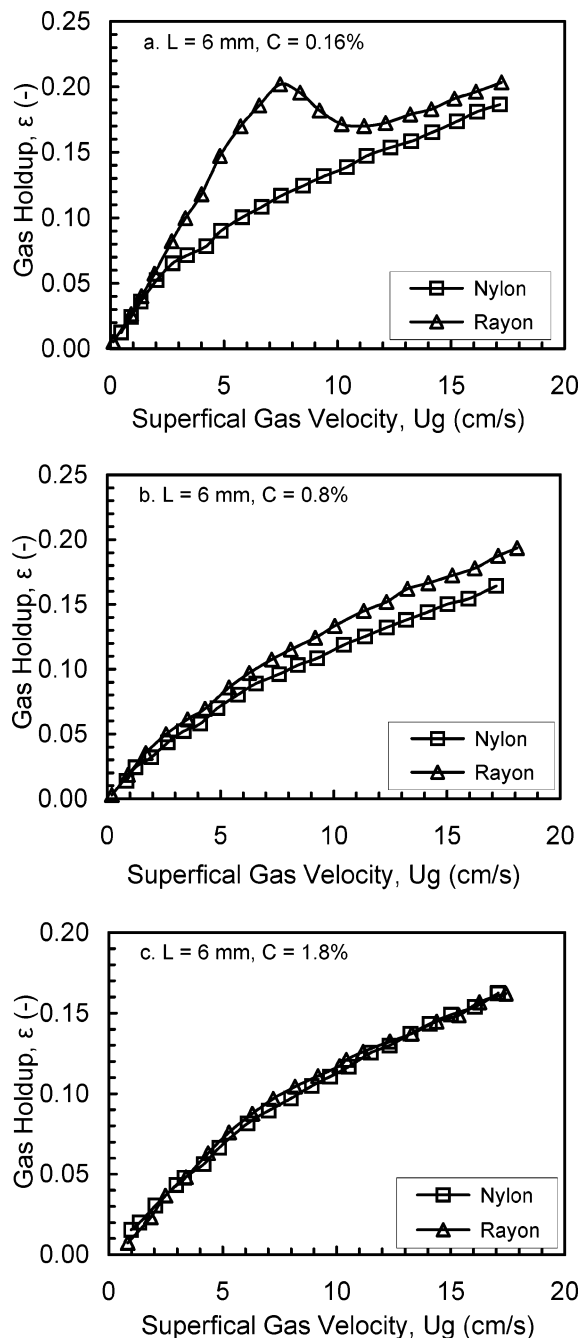


Figure 4. Gas holdup comparison of nylon and rayon fiber suspensions ($L = 6$ mm) at various fiber mass fractions: (a) $C = 0.16\%$; (b) $C = 0.8\%$; (c) $C = 1.8\%$.

the gas is shut off. Also, no bubbles are observed on the rayon fiber surface.

Studies have shown that particle wettability may also have a significant effect on the gas flow behavior in a slurry bubble column. Jamialahmadi and Muller-Steinhagen¹⁶ recorded that the addition of a small amount of nonwettable solids to an air–water system caused a considerable reduction in the gas holdup. Lower gas holdup for hydrophobic particle systems was also observed by Van der Zon et al.¹⁷ The enhancement of bubble coalescence by hydrophobic particles is also known from antifoaming studies,^{18–20} where hydrophobic particles tend to promote bubble coalescence by enhancing film rupture when two bubbles approach. In contrast, wettable particles tend to repel the gas interface, acting as a buffer between two adjacent gas

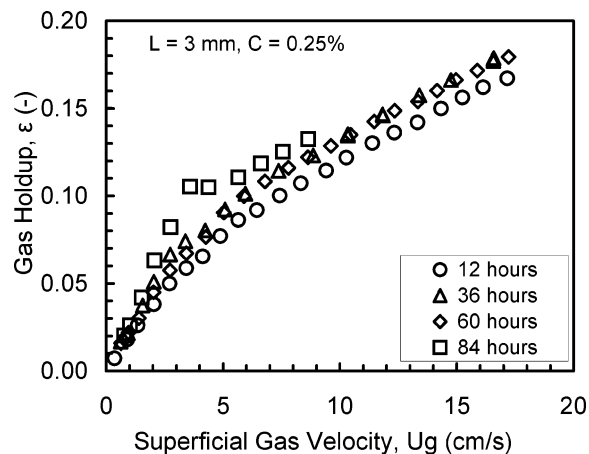


Figure 5. Gas holdup dependence on time for a nylon fiber suspension.

bubbles and resulting in a decrease in bubble coalescence.²⁰ Chen and Fan¹⁵ also showed that nonwettable particles suppress bubble breakup. Both the promotion of bubble coalescence and the suppression of bubble breakup will considerably reduce gas holdup in systems with hydrophobic solids.

The degree of affinity the fiber has to water also has an impact on the fiber–fiber adhesive force. Chauchoe and Koch²¹ showed that adhesive force played an important role in the strength of fiber flocs, where a large force made the flocs easy to form and difficult to break up. They also showed that the adhesive force of nylon fiber in a glycerin–water mixture was ~ 20 times higher than that in silicone oil and attributed this to the hydrophobicity of nylon fiber. It can be postulated that the adhesive force among nylon fibers is greater than that of rayon fiber because nylon fiber has a lower affinity to water. This is supported by the fact that attempts to uniformly disperse small mass fractions of 12-mm-long nylon fiber in water were unsuccessful; after the suspension was agitated for a period of time through bubble-induced mixing, fiber bundles were formed. In contrast, 12-mm-long rayon fiber disperses easily in water.¹⁰ Larger adhesive forces among nylon fibers also require a larger buoyant force to break through the fiber flocs, resulting in larger bubbles and a decrease in the gas holdup.

The difference in the gas holdup between nylon and rayon fiber suspensions may also be attributed to other fiber properties such as fiber flexibility that leads to different effective suspension viscosities, resulting in different gas flow behaviors. Nylon fiber is less flexible than rayon fiber,²² and this tends to lower the nylon suspension viscosity, leading to a higher gas holdup when compared to that of rayon suspensions, which conflicts with the experimental results. This suggests that the effect of other factors, like nylon fiber hydrophobicity, overshadows the effect of fiber flexibility.

Time-Dependent Gas Holdup in Nylon Fiber Suspensions. One important observation of the gas holdup behavior in nylon fiber suspensions is that it varies with the length of time the fiber is in the suspension. For example, four replicate experiments were completed with nylon fiber $L = 3$ mm and $C = 0.25\%$ over a period of 84 h after the fiber was added to the bubble column. Figure 5 clearly shows that the gas holdup varies with time and tends to increase with long-term system exposure. The first data set was taken 12 h ($t = 12$ h) after the fiber was added to the bubble

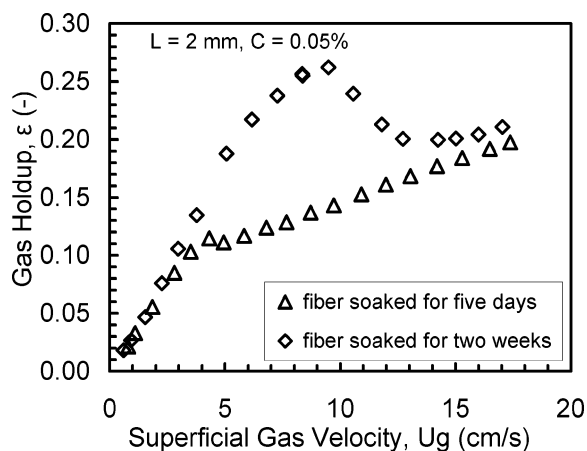


Figure 6. Effect of the nylon fiber soaking time on gas holdup.

column. Large bubbles are observed even at very low superficial gas velocities ($U_g < 0.9$ cm/s), and the gas flow regime is purely heterogeneous. The gas holdup obtained at $t = 36$ and 60 h is higher than that of $t = 12$ h, but the bubbles have no visual difference from those of $t = 12$ h. Heterogeneous flow is still observed over the entire range of superficial gas velocities. Also, no foam is observed for $t = 12, 36,$ and 60 h.

After $t = 84$ h, the gas holdup increases and the bubbles are visually smaller than those of $t < 84$ h with no large bubbles at low superficial gas velocities ($U_g \leq 2$ cm/s). Foam, which is not observed when $t < 84$ h, appears at the top of the fiber suspension surface. From Figure 5, a change in the gas holdup trend is exhibited at $t = 84$ h; this deviation is characteristic of three separate gas flow regimes (homogeneous, transitional, and heterogeneous flow).

The gas flow characteristics of nylon fiber suspensions are not only affected by the experimental time in the bubble column but also affected by the time the fiber is soaked in tap water prior to experiment initiation. Figure 6 clearly shows the difference in the gas flow behavior between a 2-mm nylon fiber soaked for 5 days and 2 weeks. The gas holdup behavior of a 2-mm fiber soaked for 5 days has the same magnitude as that of 3- and 6-mm nylon fiber at the same mass fraction of $C = 0.05\%$ (soaked for 3–5 days). However, the gas holdup of fiber soaked for 2 weeks is much higher, and a maximum gas holdup is exhibited. Although some fiber flocculation is observed at low superficial gas velocities in the fiber soaked for 2 weeks, a significant amount of fiber is uniformly dispersed in the bubble column, not adhering to other fiber or bubbles; this is not observed in the fiber that was soaked for 3–5 days.

To confirm the time-varying characteristic of the nylon material, the gas holdup in a nylon powder system was also investigated. The gas holdup data in a $C = 0.05\%$ nylon particle system, with a particle size range between 105 and 180 μm , were repeated five times within $t = 108$ h, after which the powder was added to the bubble column. The gas holdup variation is also observed in the nylon powder suspension, as shown in Figure 7. The gas holdup behavior is the same as that of the nylon fiber; that is, the gas holdup increases with time. The increase in the gas holdup with time is more apparent at intermediate superficial gas velocities, when the gas flow is in the transitional flow regime.

It is hypothesized that some nylon fiber suspension properties change with time when exposed to an air–

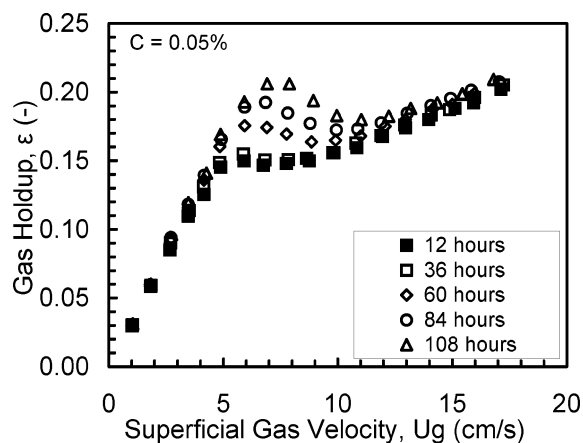


Figure 7. Gas holdup dependence on time for a nylon powder suspension.

water hydrodynamic field, and these changes affect the gas flow hydrodynamics by promoting bubble breakup and/or hindering bubble coalescence. This influences the bubble size distribution, resulting in an increase in the gas holdup in the nylon suspension. To test this hypothesis, the surface tension, electrical conductivity, total dissolved solids, and pH of the filtrate from the nylon fiber and powder suspension were measured before and after each data set. No significant change in these properties was recorded.

Several possible additional mechanisms may cause changes in the nylon fiber suspension properties during long-term water exposure that are not recorded when measuring the surface tension, electrical conductivity, total dissolved solids, and pH; these include (i) nylon fiber surface additive influence, (ii) fiber degradation, (iii) reduced fiber hydrophobicity, and (iv) deformation of the nylon fiber shape. The time-varying gas holdup caused by the nylon system changes may be attributed to one or more of these mechanisms.

Mechanism 1: Effect of Nylon Fiber Surface Additives. During the manufacture of nylon fiber, many additives may be used to satisfy industrial process requirements. For example, a spin finish will be applied to yarn to control static electricity and as an aid for further processing. These spin finishes are usually composed of a proprietary mix of a lubricant, an emulsifier, an antistatic agent, and other components.²³ Although the fibers were well washed in water before the experiment, perhaps it was not sufficient to remove all of the materials. Some of the remaining additives may dissolve in water during the experiment and change the water properties, further affecting the bubble behavior in the fiber suspension. For example, foam was observed only after several hours of bubble-column operation, and the foam appearance could be the result of nylon fiber additives leaching into the water. Also, the fiber surface characteristics and suspension filtrate chemistry may change with time because of the additives dissolving in the water, resulting in the change in interfiber forces and thus variation in the apparent viscosity of the fiber suspension. The influence of nylon surface additives may be the main source of the variation in gas flow hydrodynamics in nylon fiber suspensions.

Mechanism 2: Nylon Fiber Degradation. Nylon is a polymer, and polymers encounter various kinds of degradation throughout their lives, starting from the reactor where the polymer is synthesized and the extruder where it is processed, during service life, and

after its failure when it is discharged into the environment.²⁴ The degradation involves several chemical and physical processes accompanied by small structural changes. In the current experiment, the nylon fiber length is short, has a relatively large surface area-to-volume ratio, and undergoes long-term exposure to water and air in a complex hydrodynamic field. In this environment, several types of degradation are possible: (i) hydrolytic degradation, (ii) oxidative degradation, and (iii) mechanical degradation.

Many polymers, mainly those synthesized by the polycondensation method (like nylon), undergo hydrolysis that leads to degradation of the polymeric material by scission of the polymer backbone.¹¹ Thanki²⁴ claims that nylon fiber is prone to hydrolytic degradation in moist environments. In the current study, hydrolytic degradation would be enhanced because of the nylon long-term exposure to water. Fragments of a suitable size, broken from the main nylon chain, become water-soluble,²⁵ which could change the properties of the suspension filtrate.

All polymers are subject to degradation by oxygen, and the stability of nylon decreases in the presence of air.²⁶ Mikolajewski et al.²⁵ observed that faster oxidation occurred when nylon fiber was wet. In the current study, nylon is exposed to water and air is continuously bubbled through the suspension. Oxidative degradation may be enhanced because the rate of oxygen diffusion into the nylon fiber would increase in the bubble-induced turbulent flow field.

Mechanical energy, applied in shear, can be converted to main-chain bond energy resulting in polymer bond scission. Hunston and Zakin²⁷ and Nagashiro and Tsunoda²⁸ suggest that hydrodynamic fields can cause the decomposition of polymer macromolecules. Muller and Davidson²⁹ bubbled hydrogen peroxide through aqueous solutions of (carboxymethyl)cellulose (CMC) and suggested that CMC chains were mechanically broken because of shear forces caused by bubble-induced mixing. In the current study, the nylon is a solid of individual fiber, and it may not experience significant mechanical degradation; however, under long-term exposure to water and bubble-induced mixing forces, mechanical degradation may contribute to the observed time-varying results.

The degradation of the nylon fiber suspension may have an effect on gas flow hydrodynamics and the apparent viscosity of the fiber suspension. There is limited information on the effect of degradation on nylon fiber properties. However, Lavrenko et al.³⁰ studied the stability of poly(naphthoyleimido benzimidazole) (PNIB) fiber under atmospheric conditions and showed that the material experienced slow hydrolytic degradation of the macromolecules, leading to a drop in the intrinsic viscosity and changes in mechanical properties such as tensile strength and elastic modulus. They also showed that the decrease in molecular weight is significantly accelerated for PNIB in the powered state. It is postulated that nylon fiber would experience changes similar to those of PNIB. The gas flow behaviors observed in nylon fiber suspensions, such as increasing gas holdup with time and a more apparent gas holdup change with time in a nylon powder suspension, indirectly confirm this postulation. The time-varying gas holdup may be partly attributed to the change in the fiber elastic modulus resulting from degradation; this may change the nylon fiber deformation under the turbulence ex-

Table 1. Selected Property Variations of Nylon Fiber Soaked in Water

soaking time (h)	surface tension (mN/m)	EC (ms/cm)	TDS (ppm)	pH
6	57	0.49	330	8.7
300	46	0.57	380	7.1

perienced in a bubble column, which could affect the fiber–fiber interaction and thus the apparent fiber suspension viscosity.

To test the possibility of mechanisms 1 and 2, approximately $C = 1\%$ fiber suspension was formed in a 4000-mL beaker, and the surface tension, electrical conductivity (EC), total dissolved solids (TDS), and pH of the filtrate were measured at $t = 6$ and 300 h, after which the fiber suspension was formed (Table 1). The surface tension and pH decreased and EC and TDS increased with soaking time, which may indirectly indicate that some fiber additives leach into the water and, perhaps, the fiber has experienced some degree of degradation. The reason no change in these properties was recorded by the bubble-column filtrate sample is that the changes are relatively small, they may be damped by the large water volume and low fiber concentration, and the equipment used is not sensitive enough to record small changes.

Mechanism 3: Reduced Hydrophobicity of the Nylon Fiber. The loss of hydrophobicity of nylon under wet conditions has been observed by Tokoro and Hackam.³¹ Hydrophobicity loss of other polymers such as polyethylene under wet conditions has also been studied by Khan and Hackam.³² The enhanced dispersion of fiber in water with longer soaking time implies a reduced degree of hydrophobicity. The nylon fiber surface becomes more hydrophilic during long-term water exposure because of fiber surface additives leaching into the water, leading to an increase in the gas holdup. Although the surface tension of the suspension filtrate (i.e., gas–liquid interface surface tension) has no apparent change, the surface tension of the gas–solid and solid–liquid interfaces will change when nylon fibers become more hydrophilic. This has a significant effect on bubble hydrodynamics, hindering bubble coalescence. The loss of hydrophobicity also reduces the adhesive forces between fibers and promotes nylon fiber floc breakup, which was observed in our experiments after prolonged water exposure.

Mechanism 4: Nylon Fiber Shape Deformation. Fiber deformation has a significant effect on the fiber suspension viscosity.³³ Blakeney³⁴ found that a suspension of slightly curved fibers could increase the apparent suspension viscosity by 10–15% above that of a relatively straight fiber suspension. Joung et al.³³ provide numerical results that show fiber curvatures of between 5 and 10 degrees and have the greatest effect on the suspension viscosity, and the viscosity decreases when fiber curvatures are beyond this range. From the results of Joung et al.,³³ the time variation of the gas holdup in nylon fiber suspensions is influenced by the change in nylon fiber deformation during an experiment, leading to a change in the suspension viscosity. According to Lavrenko et al.,³⁰ fiber degradation affects fiber properties such as elastic modulus, which, in turn, affects fiber deformation. Nylon fiber deformation would continue to change during exposure in a hydrodynamic field, leading to an increase in the gas holdup with time.

Effect of Fiber Mass Fraction on Gas Holdup: Revisited. Figure 2 was obtained from data taken on

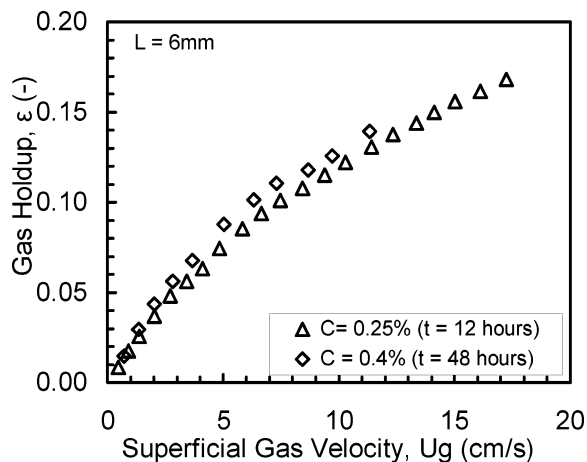


Figure 8. Time dependence of the fiber mass fraction effect on gas holdup.

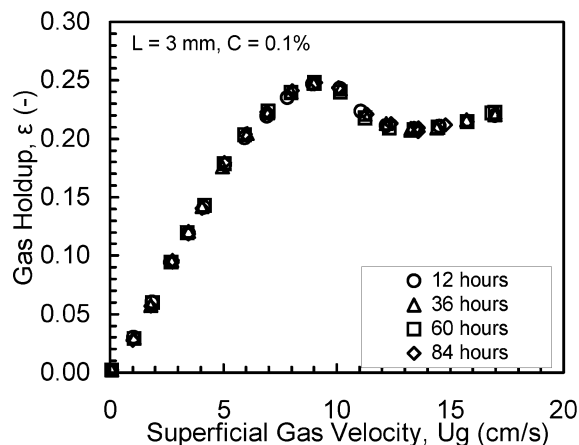


Figure 9. Gas holdup repeatability in a rayon fiber suspension.

the same day that the fiber was added to the bubble column. However, the effect of the fiber mass fraction on the gas holdup also depends on the length of time the fiber is in the column. Figure 8 shows that the gas holdup at a nylon fiber mass fraction of $C = 0.4\%$ and taken at $t = 48$ h is higher than that of $C = 0.25\%$ taken at $t = 12$ h. This conflicts with the trend that increasing the mass fraction decreases the gas holdup, as shown in Figure 2, as well as the results in rayon fiber suspensions.¹⁰ The gas holdup time independence makes it extremely difficult to study the effect of the nylon fiber mass fraction on the gas holdup because the results depend on when the data are collected.

Selected experiments were completed in rayon fiber suspensions to determine if the gas holdup in these suspensions also varies with time. Excellent reproducible results of the gas holdup in rayon fiber suspensions with $L = 3$ mm are shown in Figure 9. There is no change in the gas holdup during 84 h, after which rayon fiber was added to the bubble column, which implies that rayon fiber degradation is very slow, if it exists at all, and has no effect on the gas holdup. Thus, the gas holdup results in rayon fiber suspensions from prior work¹⁰ are reliable, and the rayon fiber is a good material to investigate the gas holdup behavior in synthetic fiber suspensions. In contrast, nylon fiber should not be used in future studies.

Conclusions

Gas holdup data taken on the first day that nylon fiber was added to the bubble column showed that the

gas holdup decreases with increasing nylon fiber mass fraction, and these results are not significantly affected by the nylon fiber length. The gas holdup in nylon fiber suspensions is much lower than that in rayon fiber suspensions at the same fiber mass fraction, which was attributed to the nylon fiber being more hydrophobic and having a larger adhesive force in water compared to rayon fiber. The time-varying gas holdup is another characteristic of nylon fiber suspensions. It was proposed that the main reason the gas holdup varies with time in a nylon fiber suspension was that nylon fiber surface additives continuously leach into the suspension water and alter the bubble behavior. Nylon fiber was prone to degradation and loss of hydrophobicity, which were also potential contributors to the time-varying rheological characteristics of the fiber suspension, especially when nylon fiber was exposed to water, air, and a hydrodynamic field for a long time period. Additional factors, such as nylon fiber shape deformation, may also contribute to the time-varying gas holdup in nylon fiber suspensions. These factors make it very difficult to interpret the effect of nylon fiber on the gas holdup. Therefore, nylon fiber is not recommended for future gas holdup studies in fiber suspensions. Excellent reproducible gas holdup data in rayon fiber suspensions indicate that rayon fiber is an appropriate material for future gas holdup studies in synthetic fiber suspensions.

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Nomenclature

- C = fiber mass fraction (%)
 EC = electrical conductivity (ms/cm)
 H = column height (m)
 L = fiber length (mm)
 M_f = fiber mass (kg)
 M_t = total mass of the fiber–water mixture (kg)
 P = pressure of the air–water–fiber suspension (Pa)
 P_o = pressure of the water–fiber suspension (Pa)
 TDS = total dissolved solids (ppm)
 t = time (h)
 U_g = superficial gas velocity (cm/s)

Greek Letters

- ϵ = gas holdup
 ρ_{eff} = effective density of the fiber–water mixture (kg/m^3)
 ρ_f = fiber density (kg/m^3)
 ρ_w = water density (kg/m^3)

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