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Visualizing Air Bubbles in Pulp Suspensions Common to Recycling Operations

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# VISUALIZING AIR BUBBLES IN PULP SUSPENSIONS COMMON TO RECYCLING OPERATIONS

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## ABSTRACT

Flotation deinking is one unit operation typically used to remove ink and toner particles from recovered paper. Air is injected into a fiber suspension and contaminant particles attach to the bubble surface. The contaminants are carried to the surface of the flotation unit by the air bubbles for eventual removal. Understanding the bubble flow characteristics is very important for effective flotation cell operation, but visualizing this process is very difficult. This study uses flash x-ray radiography (FXR) to observe air flows in repulped unprinted copy paper suspensions at consistencies as high as 5% by weight. FXR images of these flows are presented and qualitative observations are described.

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## INTRODUCTION

Gas flows in fiber suspensions occur in many areas of the paper recycling process. Steam may be injected directly into the repulper to raise the stock temperature to reduce the energy required to defiber recovered paper. Air may be entrained into the stock suspension by cavitation in mixers, pipe expansions, and pipe elbows. Air may also be entrained through improper operation of pressure screens and centrifugal cleaners. Washing may also entrain air in the suspension. However, the most common recycling process where gas is introduced into a pulp suspension is during flotation deinking, where injected gas is used to remove contaminants.

In the flotation deinking process, a gas (i.e., air) is injected into a suspension of recovered paper at a typical consistency of 0.8-1.2% [1, 2]. Contaminants with the correct characteristics may interact with the gas bubble and form a bubble/particle aggregate. If the buoyant force of this aggregate is sufficient to carry it to the surface, the contaminant will be removed from the fiber suspension. Therefore, the bubble must be large enough to rise through the fiber suspension. However, if the bubble is too large, total bubble surface area is substantially reduced for a given total gas volume. Additionally, preferential bubble rise paths, called channels, may form. These effects can significantly reduce flotation efficiency. Understanding the gas flow characteristics in these, and other types of fiber suspensions, is important for effective process operation.

The knowledge of gas flow regime is one type of gas flow characteristic that is of interest. The primary flow regimes in flotation deinking cells are either bubbly or churn-turbulent. Bubbly flow is characterized by an even dispersion of many small bubbles with minor interactions between the bubbles rising in a continuous liquid phase. In narrow diameter gas/liquid bubble columns, bubbly flow is usually assumed to occur at superficial gas velocities below 5 cm/s [3], where the superficial gas velocity is defined as the volumetric gas flow rate divided by the column cross-sectional area. Flotation deinking cells operate in this range of superficial gas velocities [4]. As the superficial gas velocity increases, bubbles coalesce to form large bubbles. These bubbles rise at a faster rate due to the increased buoyant force associated with them. The large bubbles also create turbulence as they rise. This flow regime is called churn-turbulent flow and is associated with superficial gas velocities as high as 10-15 cm/s [3]. Flow regime identification in a rectangular bubble column filled with a 0-1.5% ONP fiber suspension has recently been completed [5], and it was shown that as the fiber consistency increased, the transition to churn-turbulent flow conditions occurred at lower superficial gas velocities. Slug, annular, and dispersed annular flow regimes occur at

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higher superficial gas velocities than those associated with churn-turbulent flow and are typically found in narrow diameter bubble columns [6, 7]. These latter flow conditions are generally not found in typical flotation deinking equipment.

Churn-turbulent flow conditions may lead to a considerable amount of backmixing or flow recirculation in a bubble column [8]. This is a condition where fluid flows in the opposite direction of the bulk flow, and is also a factor in effective flotation cell operation. In upflow bubble columns, the bulk flow (liquid and gas) generally travel through the column center. If the upward movement of the bulk flow is strong enough, downward movement (backmixing or flow recirculation) of some of the flow is observed along the column walls. The magnitude of the backmixing is dependent upon the superficial gas velocity and the column diameter. Low superficial gas velocities show little backmixing, while high superficial gas velocities show intense backmixing. Additionally, small diameter columns inhibit backmixing [7, 9]. In gas/liquid/fiber systems, backmixing has been observed by Lindsay et al. [10], Heindel and Monefeldt [11], Schulz and Heindel [12], and Reese et al. [13].

Bubble size distribution is another gas flow characteristic that is important to effective flotation cell operation. Hunold et al. [14] measured bubble size in dilute fiber systems of less than 0.5% consistency 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 size in fiber suspensions has also been obtained by Ajersch et al. [15] by isolating pulp 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 assumes negligible bubble coalescence and that all bubbles present are free to rise to the surface. Bubble size measurements have also been obtained in air/water systems to calibrate air injectors used in flotation deinking studies [4]. This information was then used to relate bubble size to flotation deinking performance, although the calibration was completed in the absence of fibers. Heindel [16] has recorded bubble size measurements in ONP pulp suspensions using flash x-ray radiography. Consistencies up to 1% were investigated and it was shown that bubble size measurements obtained in a simple air/water system may not represent the actual bubble size distribution in an air/water/fiber system.

Gas holdup (or void volume or void fraction) is another important characteristic of gas flows in pulp suspensions. It is defined as the gas percent by volume in a multiphase system. A high gas holdup often implies an increase in total interfacial area between a gas and liquid and/or an increase in the gas residence time [10]. Gas holdup increases with increasing superficial gas velocity when the flow conditions are bubbly. However, when gas bubbles coalesce and churn-turbulent flow conditions are observed, the gas holdup is reduced because larger bubbles rise faster than smaller ones [17-19]. This trend has also been observed in slurry flows [8, 20] and fiber suspensions [10, 12].

Gas holdup values for a quiescent fiber system (no bulk fluid movement) consisting of clove oil or water and mechanical or chemical wood fibers have been reported by Walmsley [21]. Both the mechanical and chemical fibers decreased the gas holdup when the consistency was greater than 0.6%. Reese et al. [13] have also shown that the presence of pulp fibers in a quiescent bubble column increased bubble coalescence and reduced the overall gas holdup compared to an air water system at the same superficial gas velocity. Similar results were recorded by Lindsay et al. [10] in a cylindrical quiescent bubble column. Lindsay et al. [10] also recorded gas holdup in a cocurrent bubble column filled with either water or a 1% ONP fiber suspension, and the 1% fiber suspension had a higher gas holdup than that recorded for the water system. Schulz and Heindel [12] also used a cocurrent bubble column to record gas holdup in ONP systems at 0, 0.8, and 1.2% consistency, a range common to flotation deinking. For these consistencies, they showed that a minimum gas holdup was always recorded at a consistency of 1.2%, and a maximum was recorded at either 0 or 0.8%, depending on the superficial gas and liquid velocities.

The ability to record gas flow regimes, bubble size distributions, and gas holdup in cellulose fiber suspensions is complicated because the fibers have a density close to that of water and they can form flocs at consistencies as low as 0.3%, and continuous fiber networks at consistencies greater than 1% [22]. This generally makes the system opaque and optical visualization is limited only to the boundary regions. If probes are inserted into the fiber suspension to measure gas flow characteristics, fibers may form entanglements around the tip, altering their recorded measurements. Visualization and measurement techniques using various types of radiation can circumvent these difficulties.

This study uses flash x-ray radiography (FXR) to visualize the flow conditions in a rectangular bubble column filled with unprinted copy paper at consistencies as high as 5% by weight. Qualitative observations of these flow conditions are described in detail, and it is shown that FXR is a useful tool for visualizing gas flows in fiber suspensions common to recycling operations.

## EXPERIMENTAL METHODS

Figure 1 is a schematic representation of the experimental setup used in this study. The x-ray unit was a 300 keV HP 43733A flash x-ray system (currently supported by Primex Physics International), which generated a 30 nanosecond x-ray pulse. The fast x-ray pulse provided stop-motion x-rays of the pulp suspensions. A single 20 cm  $\times$  25.2 cm x-ray negative was exposed during the discharge of the x-ray unit. Complete details of the FXR procedures can be found in [11].

The bubble column had a rectangular cross section of 20 cm  $\times$  2 cm and was constructed with face panes of 6.35 mm clear acrylic stock. The column was 1 m tall with lead numbers affixed to both sides to indicate the column height on the x-ray film. Compressed and filtered building air was injected into the base of the column through a sintered bronze sparger with a nominal pore size of 40  $\mu$ m. This was attached to the end of a flexible air line and placed on the bottom of the column. The air line was positioned near the column wall such that it did not interrupt the bulk flow patterns. For fiber consistencies greater than 2%, the flexible air line was placed within a small diameter pipe to keep the backmixed flow from moving it to the center of the column. A fixed air flow rate of 2 slpm (standard liters per minute), corresponding to a superficial gas velocity of 0.83 cm/s, was specified for each test condition. As described, the bubble column can be likened to a graduated cylinder with a rectangular cross section. Air passed through it, but no bulk exchange of the liquid occurred (i.e., the superficial liquid velocity was zero).

The system of interest was composed of deionized water with or without unprinted copy paper. The copy paper was reslushed at a consistency of approximately 11% using a Lamort high consistency pulper. The pulp consistencies imaged in this study ranged from 0.5 to 5% (in 0.5% increments), which covers a range typically found in recycling unit operations. The various pulp consistencies were prepared by diluting samples of the high consistency stock with deionized water. The bubble column was charged by filling it from the top with 3.2 L of the desired fiber slurry, corresponding to a fluid column height of 80 cm. This allowed for fluid expansion in the bubble column during air injection. After the air was turned on, a waiting period of approximately 10-15 minutes allowed the flow to reach quasi-steady-state conditions, at which time x-rays were taken at one of four column positions.

## RESULTS

Flash x-rays were obtained at four locations of a rectangular bubble column filled with repulped copy paper at consistencies of up to 5%, in 0.5% increments. For comparison purposes, Fig. 2 displays radiographs of the four column positions for an air/water system. The images at each column position were taken at separate time intervals, and this figure represents a composite of the gas flow conditions. The gaps between radiographs are due to the fixed locations where the FXR images were acquired. The air line is apparent on the left-hand side of each radiograph, and the location of the sintered bronze sparger is schematically shown at the base of the column. The actual x-ray images of each position in Fig. 2 encompassed a 20 cm  $\times$  20 cm column area. Approximately 2.5 cm of film extended beyond each side and included the lead position indicators and a radiograph identification label. These regions have been digitally removed from each position to enhance the image clarity.

The dark regions at each position represent air bubbles. At the fixed air injection rate of 2 slpm, the flow conditions would be considered bubbly or beginning the transition from bubbly to churn-turbulent flow. The bulk of the bubbles rise in a serpentine pattern that oscillates from one side of the column to the other. Figure 2 shows this pattern starting toward the right-hand side in Position 1. The start of the serpentine pattern periodically oscillates from the right-hand to the left-hand side of Position 1. Backmixing is also visually observed with these operating conditions. The bubbles on the left-hand side of Position 1 in Fig. 2 are caught in the backmixed flow. These bubbles eventually become entrained in the bulk upward air flow.

Some of the bubbles in the radiographs appear to group together and rise as a single bubble. It is hypothesized that these bubbles will coalesce to form large single bubbles if the thin liquid film between the bubbles has enough time to rupture before the bubble group reaches the surface. Larger bubbles at Position 4 compared to those at Position 1 support this conclusion.

The column was initially charged to a fluid height of 80 cm. The air/fluid interface identified in Position 4 is much higher than the original charge level due to the air bubbles in the system (i.e., gas holdup). The exact gas holdup value for these conditions is difficult to identify with a single radiograph of Position 4 because the air/fluid interface fluctuates. Additionally, as shown in Position 4 of Fig. 2, the air/fluid interface is not smooth and depends on the size of the bubbles breaking the surface.

When as little as 0.5% copy paper is added to the column, the bubble size and shape change considerably (Fig. 3). Many small bubbles are still present, but are fewer in number due to the increase in size and number of the large bubbles. The large bubbles rise in a serpentine pattern entraining the smaller bubbles as they rise. Backmixing is also very evident during visual inspection, but difficult to capture during the stop-motion flash x-ray exposure. The flow regime for these conditions would be considered in the transition region between bubbly and churn-turbulent flow or just in the churn-turbulent flow regime. Therefore, the presence of 0.5% copy paper fiber causes an early transition to churn-turbulent flow when the air flow rate is constant.

One feature of the FXR technique is the ability to record the bubble shape of fast-rising bubbles. The large bubbles are generally spherical-capped bubbles (i.e., bullet-nosed), but variations are also observed. Some of the bubbles in Fig. 3 are also large enough to encompass the entire column depth of 2 cm. The deformation of the air/liquid interface as a result of a large bubble about to break the surface is also clearly evident in Position 4 of Fig. 3.

Figure 4 shows the composite radiographs for the bubble column filled with 1% copy paper consistency. A fiber network begins to form at this consistency, which can restrict bubble movement. A bubble can break through this network only if it is large enough (i.e., has a sufficient buoyant force). This causes considerable bubble coalescence to take place. Since the air flow rate is constant, the resulting large bubbles reduce the number of small bubbles in each radiograph when compared to Figs. 2 and 3. As shown on the right-hand side of Position 1 in Fig. 4, coalescence between two relatively large bubbles may also take place. A large spherical-capped bubble has another large bubble caught in its wake. This reduces the drag force on the trailing bubble, allowing it to rise faster. It will eventually catch the leading bubble and coalesce with it, forming an even larger bubble. These large bubbles still rise in a serpentine pattern but are generally confined to the central region of the column. This flow regime is considered to be fully churn-turbulent flow.

At 1.5% copy paper consistency, the bubble rise patterns change (Fig. 5). Instead of oscillating back and forth in a serpentine pattern, the main air flow rises in an almost vertical path. This is the result of a strong fiber network. The bubbles are also very large and rise very quickly, creating paths of low rise resistance that subsequent bubbles follow. This process is called channeling. The location of these channels is not static due to the constant shifting of the fiber network caused by the rising bubbles. The absence of any large bubbles in Position 4 is the result of no large bubbles passing through this region during the 30 nanosecond x-ray exposure. They still pass through Position 4, but were not captured in this particular radiograph.

Similar results are observed as the copy paper consistency increases to 2 and 2.5%. The fiber network continually strengthens, and the number of small bubbles decreases while the number of large bubbles increases.

At a copy paper consistency of 3% (Fig. 6), two changes take place. First, turbulent backmixing is no longer visually observed, but a steady downward fiber movement along the column walls pushes the flexible air hose toward the column center. To prevent the hose movement, it was placed within a pipe that was placed along the column wall. This results in the wide dark line along the left-hand side of the column in Fig. 6. This did not affect the downward fiber movement along the column wall. Second, the fiber network begins to hold some of the large bubbles in place for a period of time before other bubbles coalesce with the stationary bubble and/or the fiber network shifts. This results in some column positions with only a few bubbles (Positions 1 and 4 in Fig. 6), while other column positions contain many (Position 2 in Fig. 6). It is hypothesized that some of the large bubbles in Position 2 will coalesce with

others, creating very large bubbles that rise very fast. The fast rising large bubbles coalesce with other bubbles and also cause the fiber network to shift, freeing other trapped bubbles.

Another significant change in flow conditions is observed when 3.5% copy paper consistency is in the bubble column (Fig. 7). The bubbles are very large and some span the entire column depth. The fiber network is dense enough in some areas that some of the large bubbles in these regions do not span the entire column depth. Rather, a portion of the bubble shape acquires the shape of the fiber network as it moves through it. This was visually observed and produced gray scale variations on the bubble radiographs. However, this was difficult to reproduce when a composite image was digitized and reduced for Fig. 7.

At this consistency, the upward air movement carries a portion of the stock (primarily water) to the surface. This causes the fiber to move toward the column bottom, where the local consistency increases because the fibers get caught in the fiber network. Therefore, a consistency gradient is created where the overall column consistency is 3.5%, but locally, the consistency is higher near the column bottom and lower near the column top. This causes a change in flow conditions at the column bottom. The fiber network is very dense on the bottom of the column and makes it difficult for discrete air bubbles to rise through it. Discrete air channels are formed instead to allow the air to pass through the column bottom (Position 1 in Fig. 7). The air channels are semi-static and remain active for periods of time ranging from a few seconds to a few minutes. Before a channel closes, another channel becomes active. We define this flow regime as discrete channel flow. Once the air channels reach a region in the bubble column that has a low enough local fiber consistency, individual air bubbles form as shown toward the top of Position 1. Above Position 1, the flow remains churn-turbulent.

As the average column consistency increases to 4 and 4.5%, the height over which discrete channel flow conditions are observed increases. Above this height, individual air bubbles are still observed.

Figure 8 displays radiograph composites for 5% copy paper, the highest consistency addressed in this study. Discrete channel flow is observed through Position 1 and 2 and into the lower portion of Position 3. Some bubbles are also trapped in these regions and result from the channels breaking down. When this happens, a portion of the remaining air may become trapped and remain stationary until a new nearby channel forms. This results in the chaotic air flow patterns observed in Position 1. Near the top of Position 3, discrete air bubbles form and rise in a manner characteristic of churn-turbulent flow.

The effect of copy paper consistency on the bubble flow characteristics is summarized in Fig. 9, which shows the Position 2 radiographs for all consistencies addressed in this study for a fixed air injection rate of 2 slpm. In the air/water system (0%), bubbly flow is observed. The transition to churn-turbulent flow is recorded at 0.5% consistency. Fully churn-turbulent flow is observed in the 1-2% consistency radiographs. In this range, very large bubbles are recorded and create the churn-turbulent flow conditions. Additionally, some small bubbles are also recorded but the frequency decreases as the consistency increases. At 2.5% copy paper, the flow is still churn-turbulent, but very few, if any, small bubbles are captured in the radiograph. Small bubbles return at 3% copy paper consistency, but they are actually trapped in the fiber network and remain suspended until they are entrained by a larger bubble. At 3.5% consistency, discrete channel flow is observed in Position 1 (i.e., Fig. 7), while churn-turbulent flow is captured in Position 2. Discrete channel flow is recorded near the lower portion of Position 2 when the consistency is 4%. At the higher consistencies, discrete channel flow is observed throughout Position 2. These radiographs clearly show that the gas flow characteristics change considerably as the copy paper consistency increases. The flow regime changes from bubbly to churn-turbulent to discrete channel flow. The air bubbles also become larger and less numerous, and the flow becomes more heterogeneous. All these effects are detrimental to efficient contaminant removal by flotation deinking.

## CONCLUSIONS

Flash x-ray radiography was used in this study to visualize air flows in fiber suspensions of unprinted copy paper. Consistencies as high as 5%, in 0.5% increments, were investigated, while the air injection rate was fixed at 2 slpm. X-ray composite images of the flow conditions and qualitative observations of these flows were presented. It was shown that for a fixed gas flow rate, the gas flow regime in a fiber suspension changes from bubbly to churn-

turbulent to discrete channel flow as the fiber consistency increases. Additionally, the FXR technique has been shown to be a valuable tool to visualize gas flows in fiber suspensions common to recycling operations.

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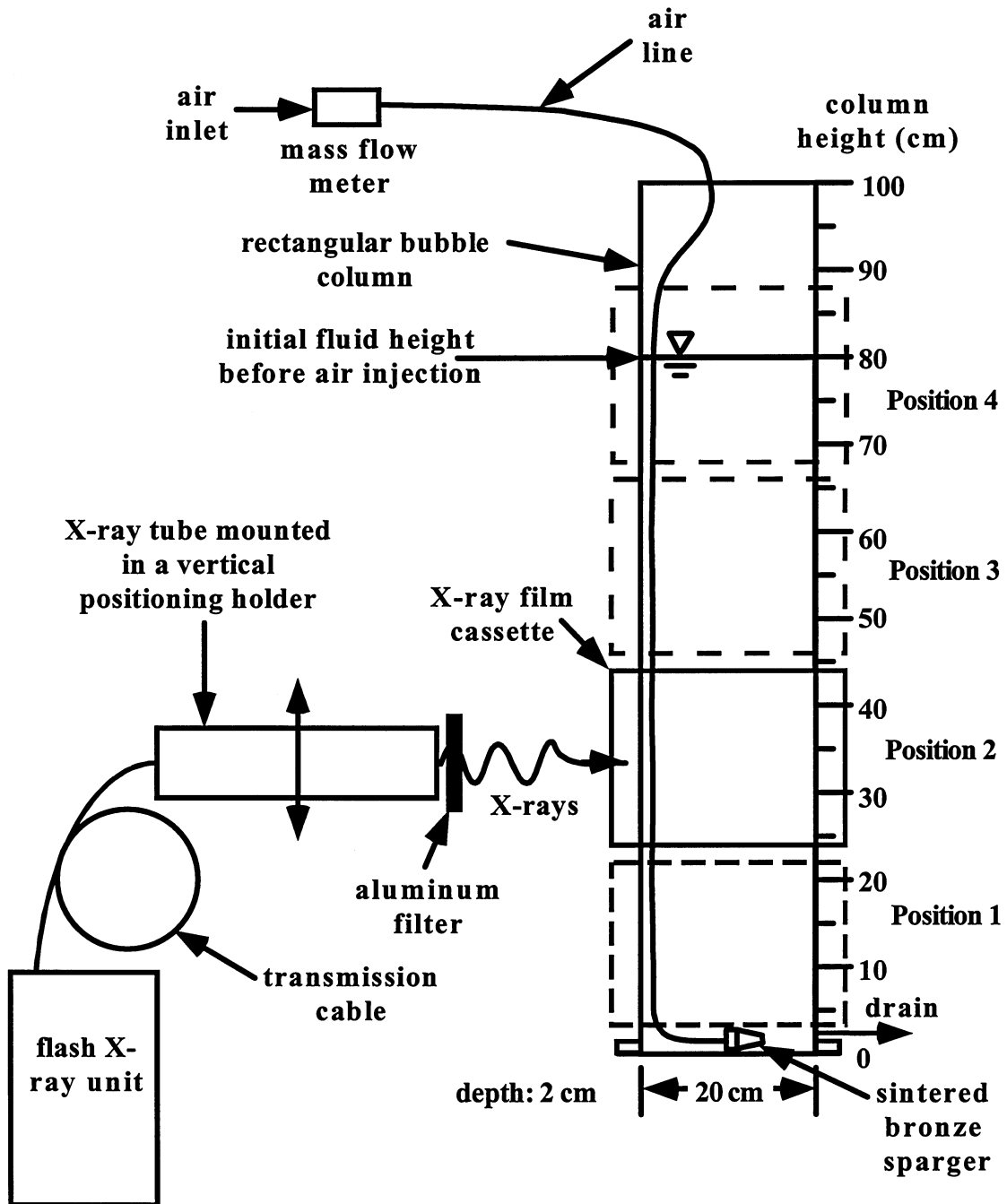


Figure 1: Schematic diagram of the bubble column and the flash x-ray unit.

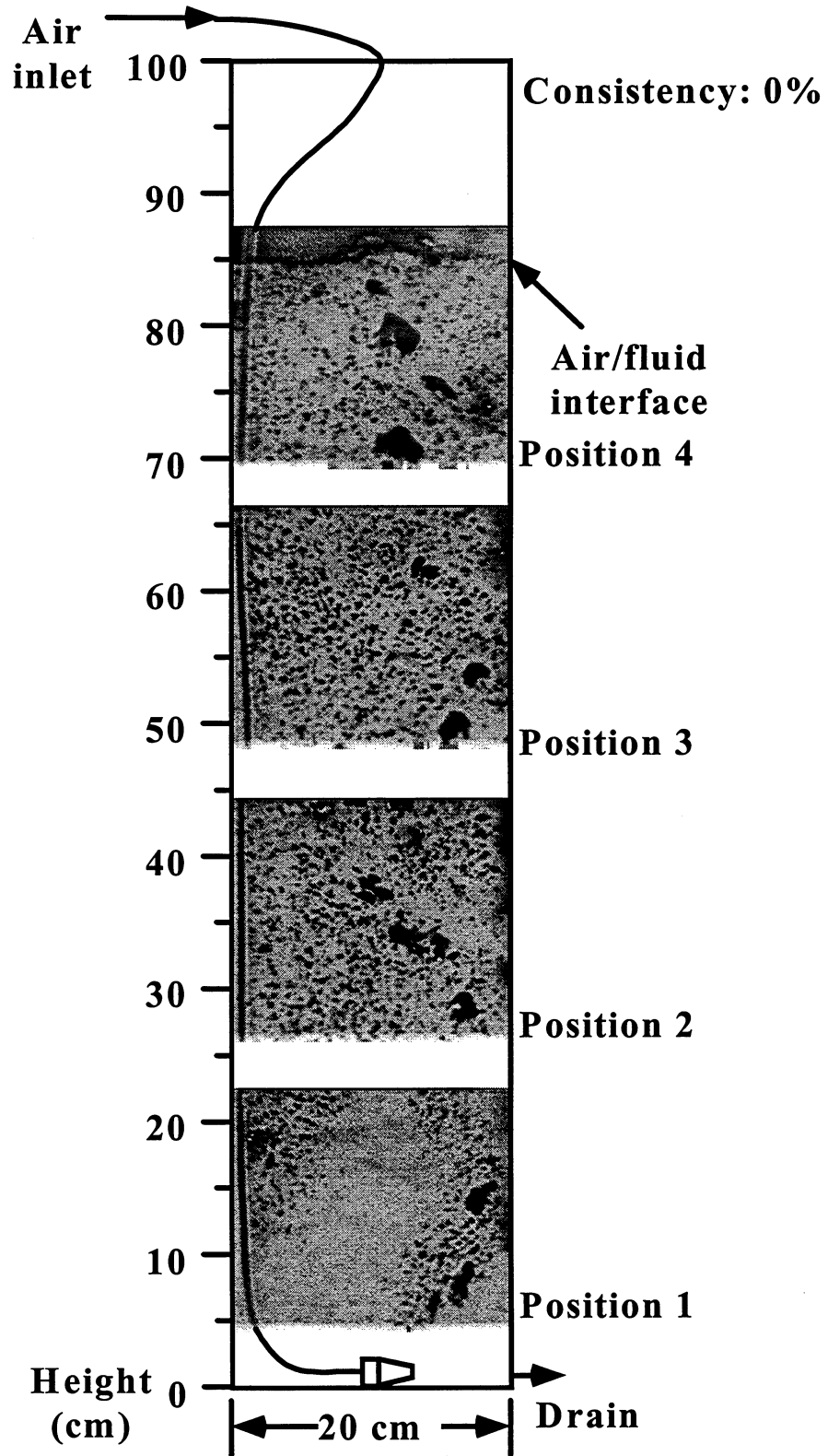


Figure 2: FXR composite of the air flow in a water-filled column (the dark regions are air bubbles).

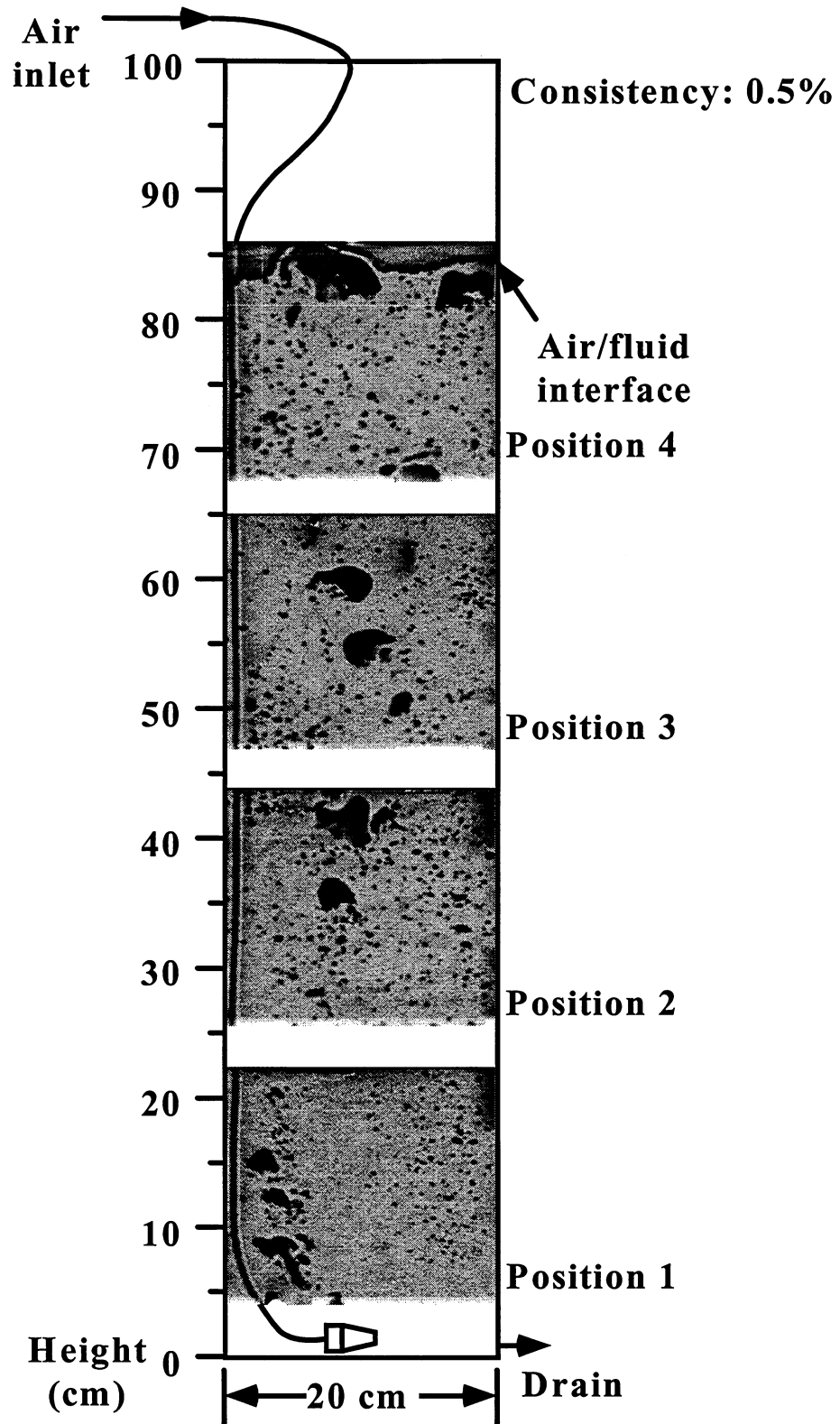


Figure 3: FXR composite of the air flow in a 0.5% copy paper system (the dark regions are air bubbles).

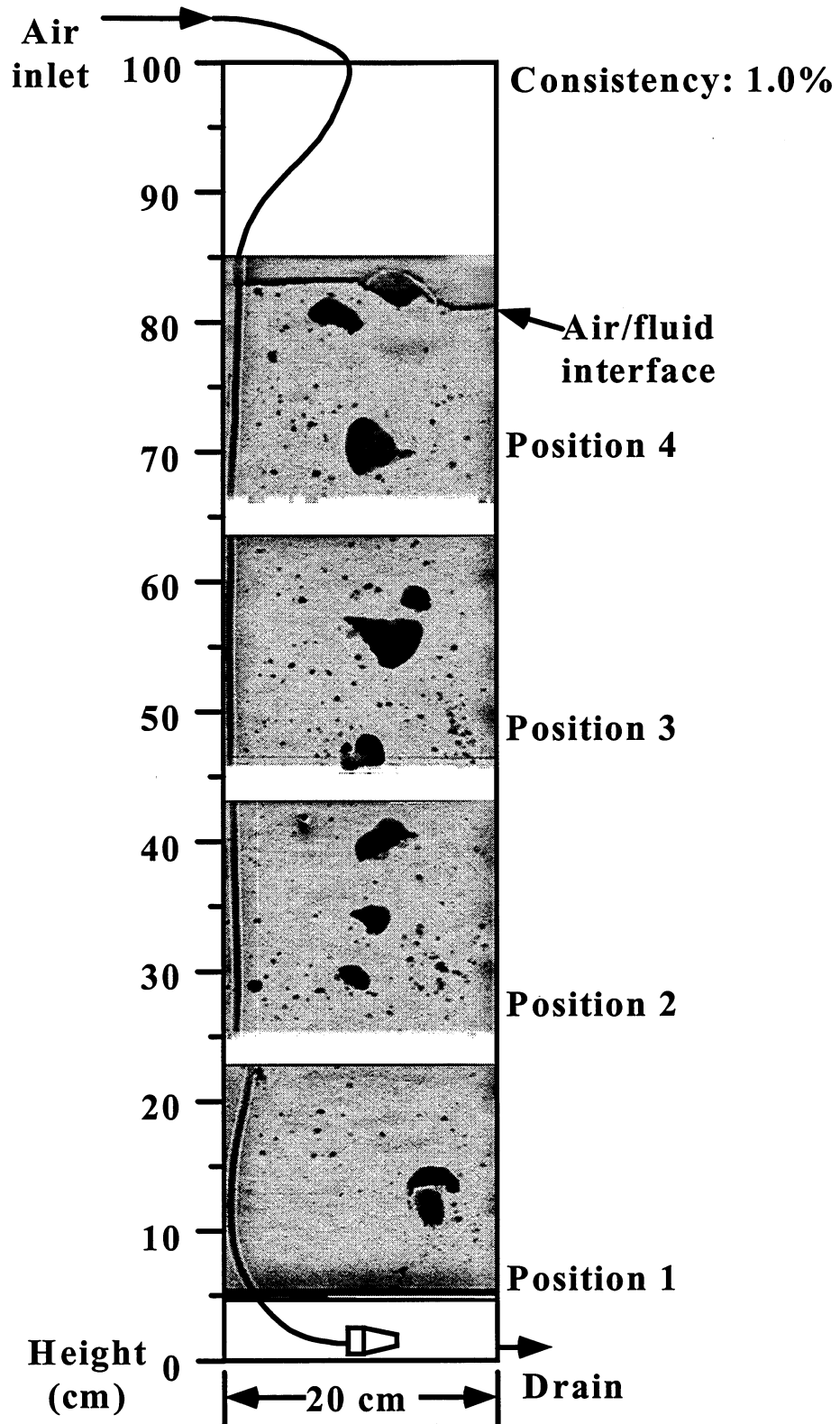


Figure 4: FXR composite of the air flow in a 1% copy paper system (the dark regions are air bubbles).

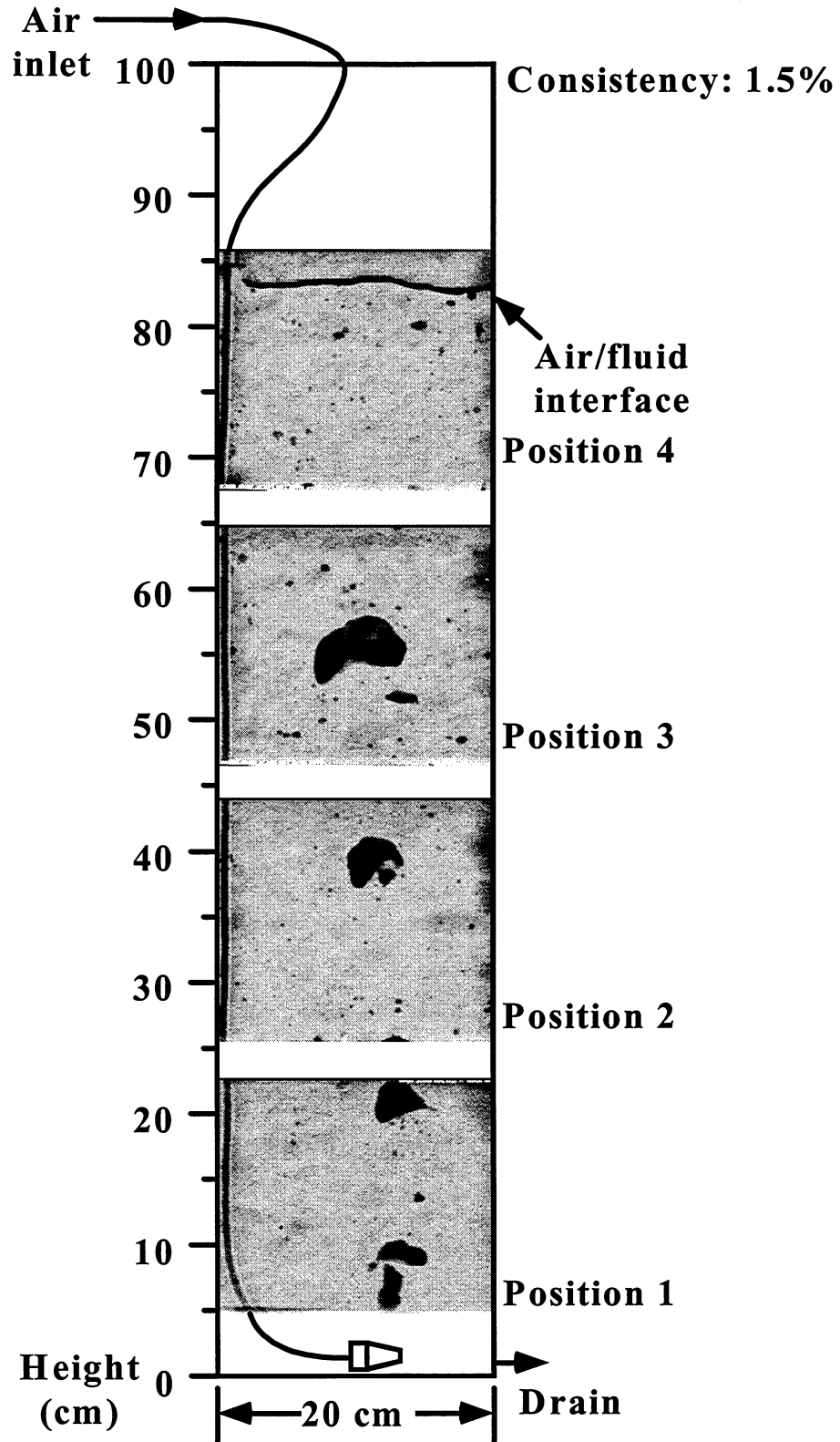


Figure 5: FXR composite of the air flow in a 1.5% copy paper system (the dark regions are air bubbles).

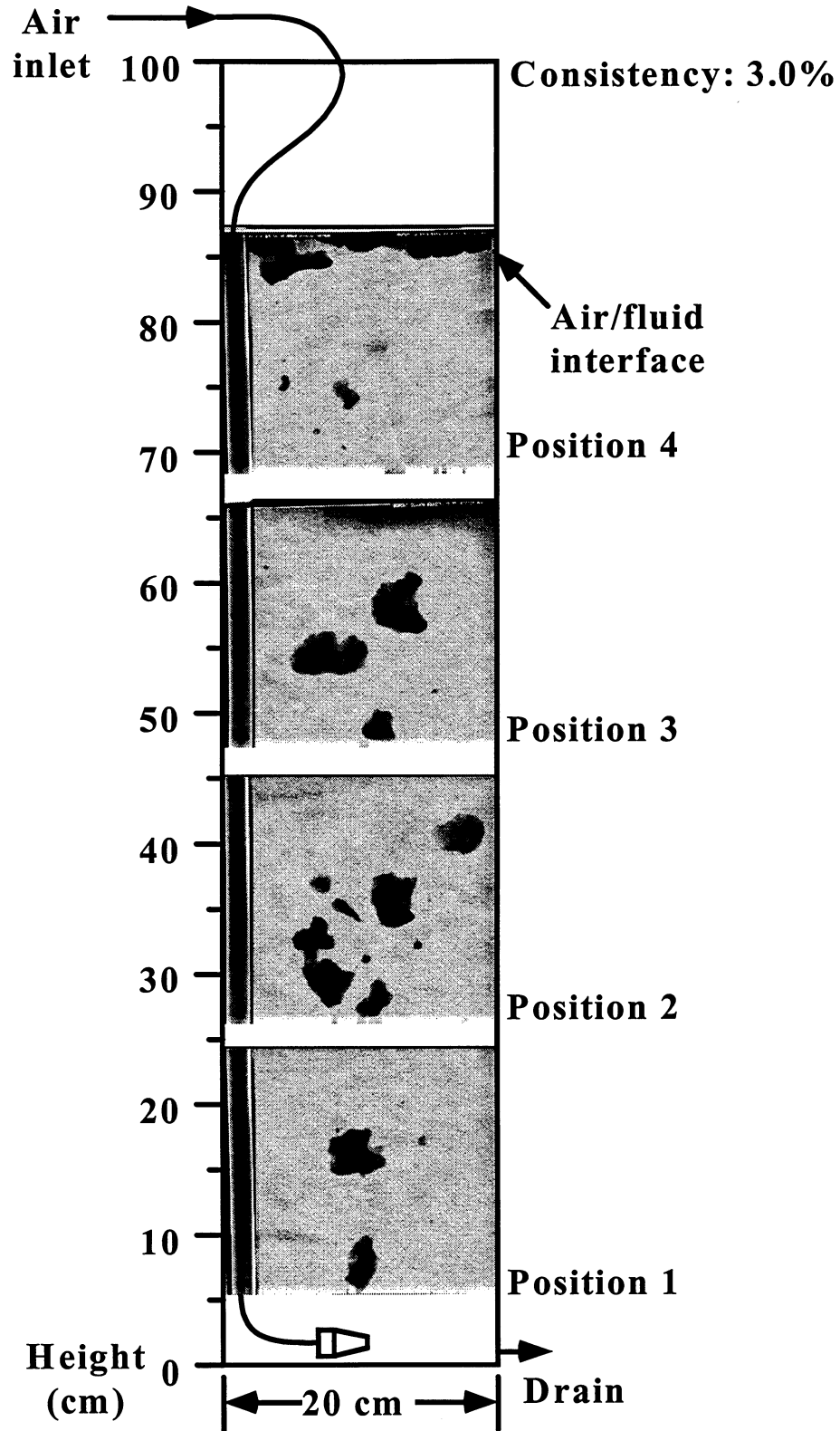


Figure 6: FXR composite of the air flow in a 3% copy paper system (the dark regions are air bubbles).

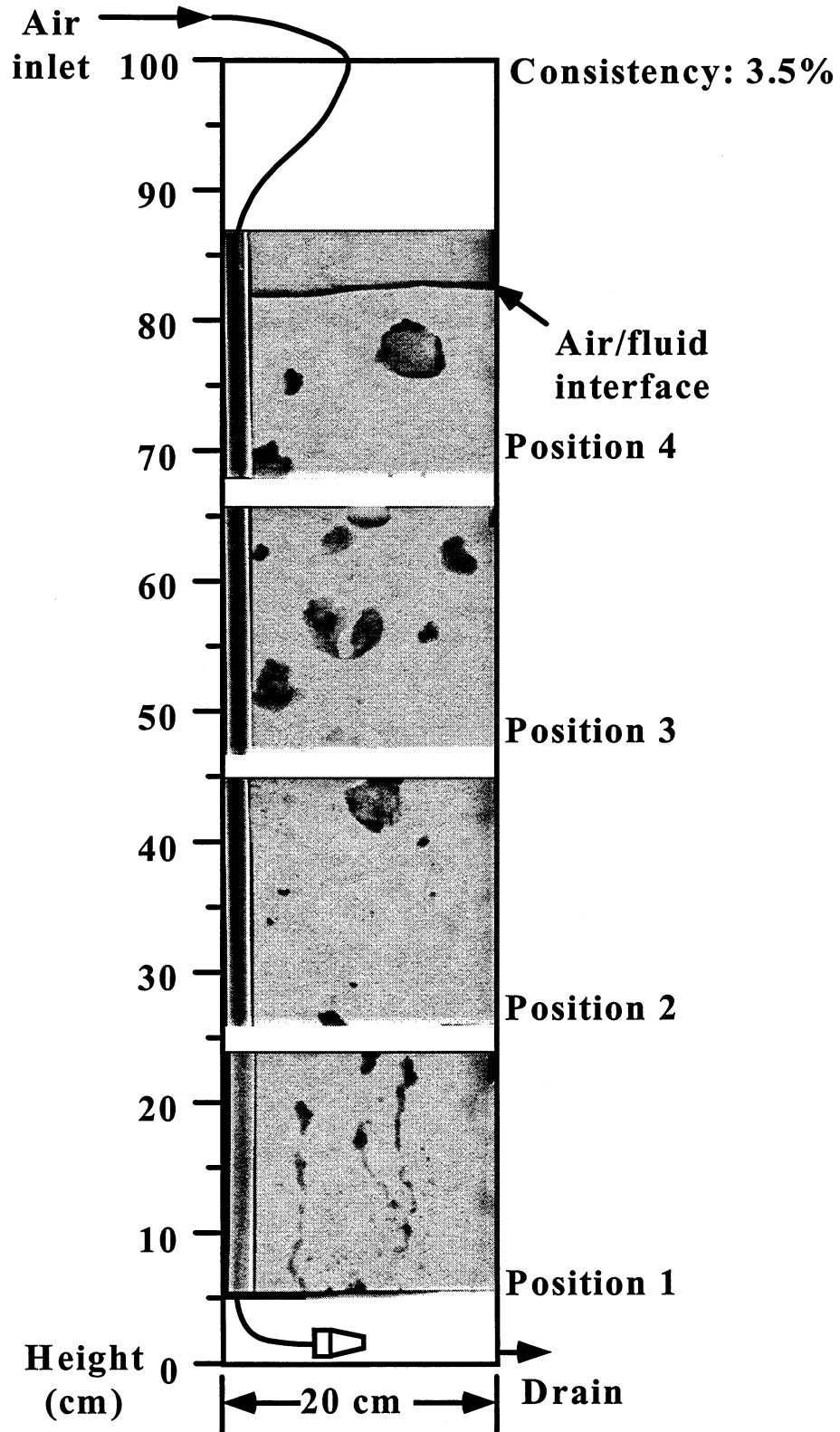


Figure 7: FXR composite of the air flow in a 3.5% copy paper system (the dark regions are air bubbles).

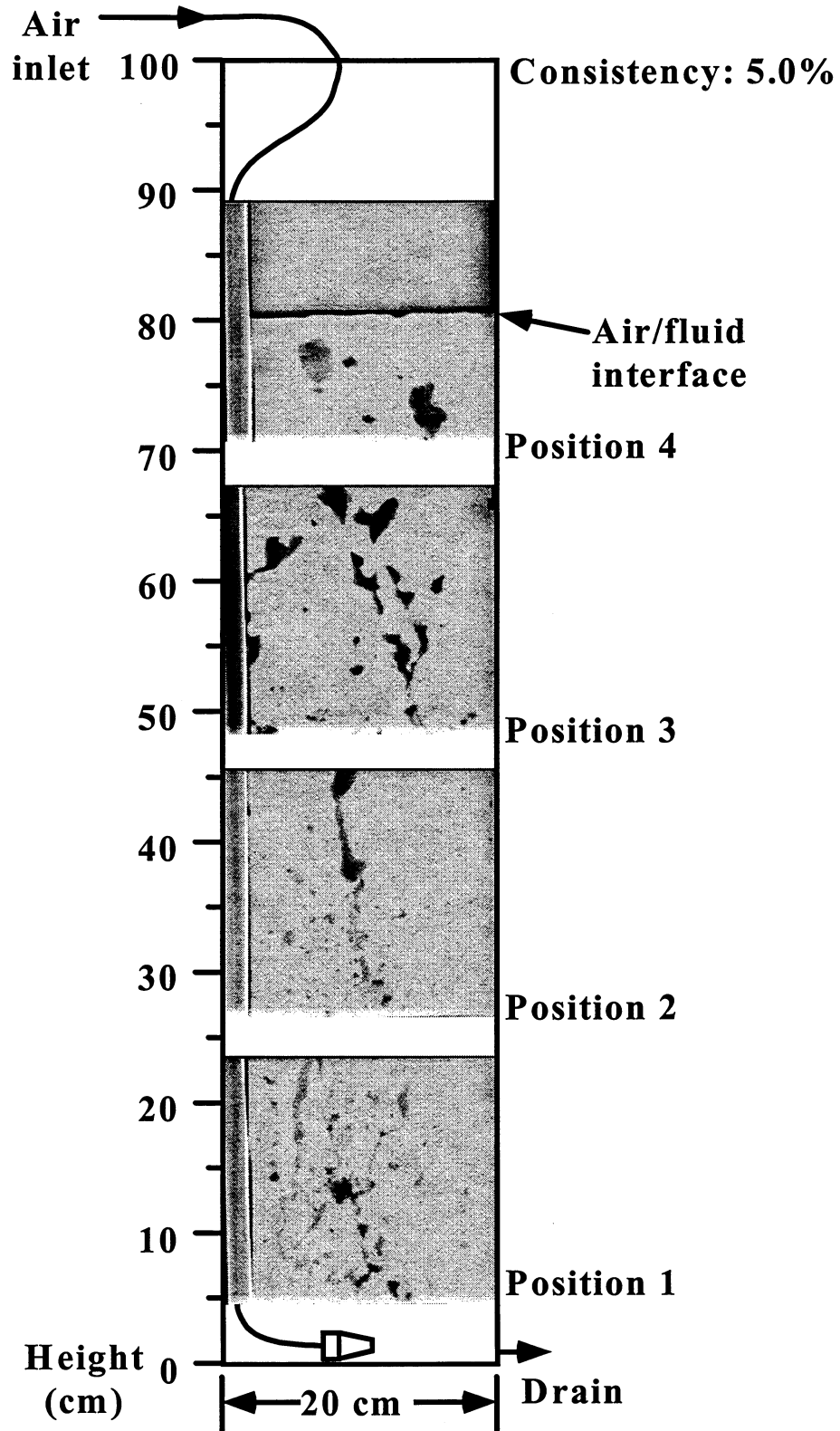
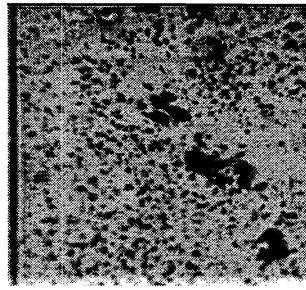
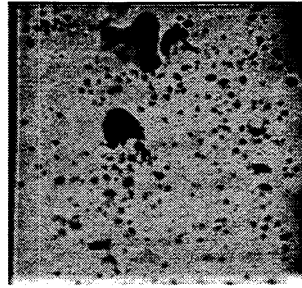


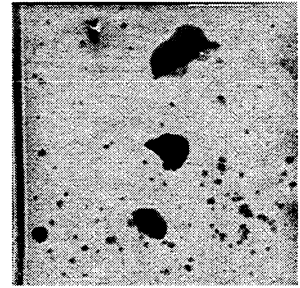
Figure 8: FXR composite of the air flow in a 5% copy paper system (the dark regions are air bubbles).



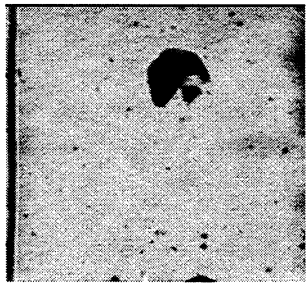
**0% copy paper**



**0.5% copy paper**



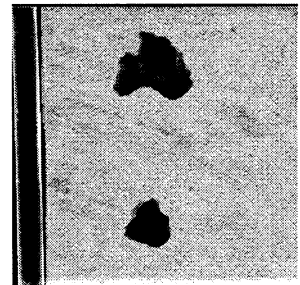
**1% copy paper**



**1.5% copy paper**



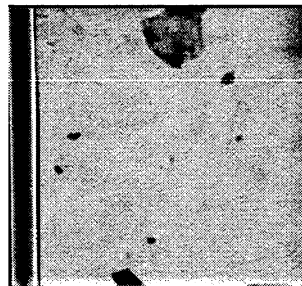
**2% copy paper**



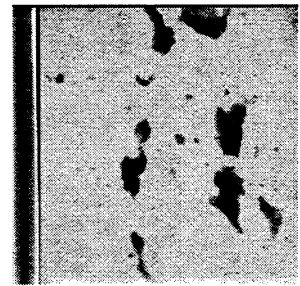
**2.5% copy paper**



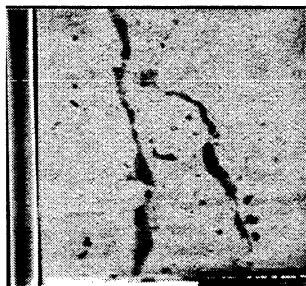
**3% copy paper**



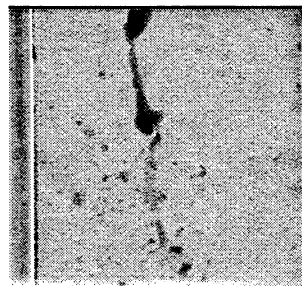
**3.5% copy paper**



**4% copy paper**



**4.5% copy paper**



**5% copy paper**

Figure 9: Gas flow comparisons at Position 2 for all copy paper consistencies addressed in this study.

