Response of Aggregate Structures to Hydrodynamic Stress

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Floc breakage is generally undesirable in processes employing coagulation as a component of the solid-liquid separation because it reduces process efficiency. This is particularly true in energetic cases because the very small fragments produced tend to remain entrained or suspended in the liquid medium. One approach to avoiding floc breakage is obvious, involving reduction of relative fluid motion as the aggregates grow in size. This idea has appeared in the literature and has been referred to as the "tapered" velocity gradient. Optimal flocculation performance, however, requires compromise since both floc growth by interparticle collision and floc breakage by hydrodynamic stress are consequences of relative fluid motion. Unless the mechanisms of disintegration and the threshold levels of stress are identified, a blind effort to reduce mixing intensity or velocity gradient through the coagulation process is as likely to have adverse effects as beneficial ones.

The first serious consideration of floc breakage from anything other than an operational point of view was the work of Healy and La Mer (1964). They proposed a mechanism for the removal of individual primary particles from the parent aggregate's surface through the action of shear stress. At that time, the energetics of such a process in turbulent flows typical of flocculation had not been contemplated, and thus shear erosion was considered plausible by many. Later study made it clear, of course, that the very small-scale fluid motions required for this process had so little energy that the mechanism was not realistic; nevertheless, the idea that breakage occurred by small particle erosion persisted well after key concepts from the statistical theory of turbulence were widely known among workers in this area.

One of the first experimental studies of floc breakage was reported by Hannah et al. (1967), in which flocs were drawn through a small orifice and the sizes of the fragments produced were taken as indicators of floc strength. The local velocity near the orifice increased from 0.3 to 518 cm/s over a distance of only 1 mm, producing a strain rate that certainly exceeded 5,000 s^{-1}. The data obtained indicated that polyelectrolytes could be used to increase floc strength, but did not provide any direct measure of that increase.

Smith and Kitchener (1978) devised a method by which the adhesion of individual particles to a smooth plate was measured and correlated to floc size produced in a Couette apparatus. The data obtained consisted of a fraction of glass beads remaining attached as a function of experienced force and the size distributions measured at various t for the flocculation experiments. No quantitative conclusions regarding floc strength or binding force could be formulated.

Matsuo and Unno (1981) carried out experiments in which flocs, formed in a paddle-agitated flocculation basin, were introduced into a turbulent pipe flow to experience breakage. The particle diameter corresponding to the 50% cumulative volume fraction was determined, and hot-film anemometry was employed to characterize the turbulent pipe flow. Yield stress (τ_y) values were calculated using expressions for relative velocity in both the dissipation and inertial subranges, and the latter depended on estimates for the dissipation rate per unit mass, ϵ. The problem with this, which is common to a number of other studies, is that τ_y must be inferred from other data.

Glasgow and Hsu (1982) reported an experimental investigation in which kaolin-polymer flocs were introduced into the thin shear layer associated with a turbulent jet. The resulting deformation and breakage process was recorded using multiple-flash macrophotography. The forces acting on the aggregate structures at the moment of disintegration were characterized from the photographic record, and in this manner a breakage theshold for flocs was established. A particularly valuable aspect of this study was determination of the breakage mode, that is the number of fragments produced by the breakage event. This was one of the first investigations to indicate directly the force required to disrupt certain types of floc structures.

Wagle et al. (1988) reviewed the findings of Lee and Brodkey (1987), who studied the dispersion of pulp flocs in a turbulent Couette flow environment. Wagle et al. noted that two major breakage mechanisms were observed—massive fragmentation and a small-scale erosion process in which fiber components were stripped from the floc surface. They also stated that the erosion process appeared to be an exponential decay in which the rate constant was a linear function of the stress arising from the flow field. The same study also reported the times required for complete dispersion of aggregate structures; a wide distribution was noted and attributed to the stochastic nature of the process and variations in the characteristic strengths of the flocs.

Bache and Alani (1989) described an experimental technique in which a vibrating column of water was used to assess the strength of clay-alum flocs. The experimental apparatus consisted principally of an acrylic plastic cylinder, 2 cm on each side and 25 cm high. An oscillating pad was located at the bottom of the column, connected to a mechanical vibrator and driven by a sine wave generator at frequencies ranging from 15 to 25,000 Hz. The power output could be regulated between 0 and 25 W. Flocs were introduced at the top of the apparatus and allowed to settle, experiencing an increasing level of power dissipation while approaching the oscillating pad. The resulting breakage events were observed photographically, and the stress experienced by the aggregate could be estimated from its position (and the characterization of the spatial distribution of dissipation rate). This study is one of the very few in which floc strength or binding force can be directly assessed.

Higashitani et al. (1989) examined the breakup of small agglomerates formed from 90-μm plastic spheres in flow approaching an orifice. Stroboscopic photography was used to record the breakage events, and the study revealed that breakage occurred before, not in or after, passage through the orifice. Estimation of the local velocity gradient allowed the force experienced by the aggregate during disintegration to be characterized. This work represents another one of the few direct studies of floc breakage; the available data are so limited that it is impossible to apply them to coagulation process improvement. For this reason, we have undertaken a new experimental study of floc breakage phenomena.

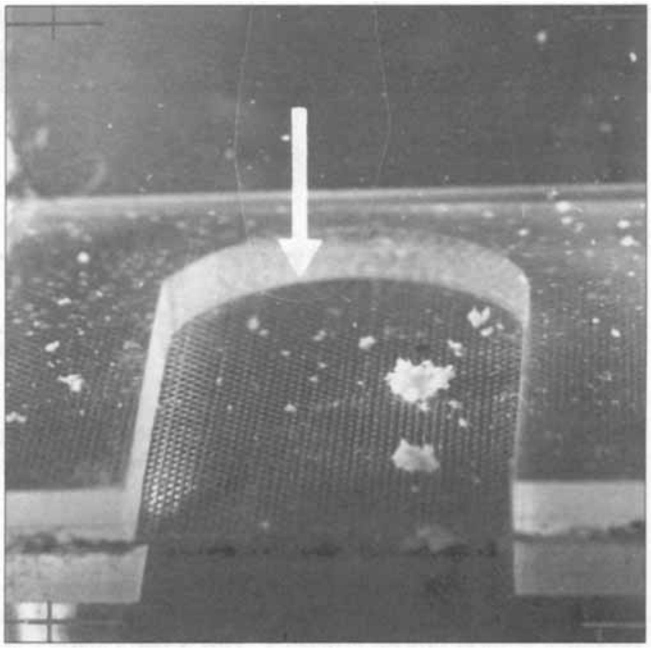

Figure 1. Acrylic plastic test chamber for floc disintegration showing a large kaolin-polymer aggregate in position upon the stainless steel mesh.

Experimental Flow Chamber

The work described here was conducted in an acrylic plastic chamber with an external cross-section of 25 cm^2 and an overall height of 30.5 cm. The internal width, depth and height were 3.8, 3.8 and 29 cm, respectively. The test chamber was divided into two equal volumes by the frame supporting the stainless steel mesh; the apparatus in Figure 1 shows several kaolin-polymer flocs that are at rest upon the mesh. The flow direction is from top to bottom as indicated by the arrow, around (over) the floc and through the supporting screen. The mesh or gauze exposed to the flow field was 1.9 cm wide and about 3.4 cm deep, yielding an area of about 6.3 cm^2, and the mean size of the *square* mesh openings was about 0.0269 cm. The actual wire diameter in the gauze was about 0.0123 cm. Obviously, in the absence of hydrodynamic forces, any particle larger than about 300 μm diameter would be retained by the mesh.

The top of the test chamber was connected to a constant-head tank, and the flow rate through the apparatus was regulated by changing the vertical position of the discharge line with a scissors jack. The range of volumetric flow rates possible with the described configuration was about 5 to more than 190 cm^3/s corresponding to mean velocities through the stainless steel mesh of 1 to at least 30 cm/s. Reynolds numbers based on the hydraulic radius of the mesh assembly could therefore range from about 240 to approximately 8,700.

The test chamber was illuminated from the left side so that the behavior of aggregates lying upon the wire gauze could be observed with a Canon E640 8-mm video camera. This camera is equipped with a high-speed shutter that allows fast action scenes to be viewed clearly during playback. Increases in flow rate were achieved by lowering the level of the discharge line, and a pointer attached to the top surface of the jack made it possible to simultaneously monitor the flow rate during the breakage experiments. In typical experiments, the flow rate would be increased until disintegration was observed; the remaining fragments would be washed from the screen and the entire process repeated.

Slow-motion playback of the video tape made it possible to analyze the parent floc size, classify the severity of the breakage event, and determine the velocity at which fragments were convected away from the supporting mesh. The nature of the data being collected was such that the existing image analysis equipment in the laboratory was of no use—all of the described measurements were made manually. It would be understatement to describe the data collection process as tedious.

Hydrodynamic Evaluation of the Apparatus

Flow visualization was used in preliminary studies of the floc test chamber to qualitatively examine the flow field both above and below the stainless steel mesh. At a Reynolds number of 1,084, convergence of the flow in the vicinity of the screen support assembly and the expected vortex structures in the upper corners were noted. This is in contrast to the extremely uniform flow seen beneath the mesh; the observed order is broken only by vortices located at both sides of the downwards-directed stream approximately 3 to 3.8 cm below the screen. Data obtained from these studies bear out the general impression that flow beneath the mesh at modest Reynolds numbers was quite uniform, corresponding very closely with the mean velocity through the screen as determined from the volumetric flow rate. At only slightly larger Reynolds numbers, however, flow visualization revealed far more complicated flow patterns. At a Reynolds number of 1,450, energetic vortical structures

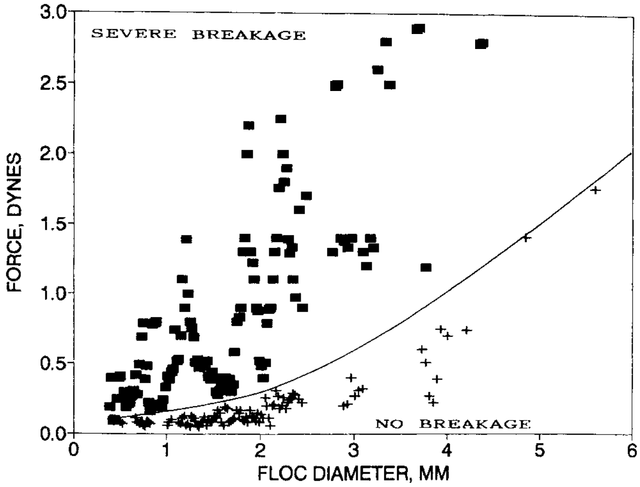

Figure 2. Breakage envelope defined by video record of 225 events in the floc test chamber.

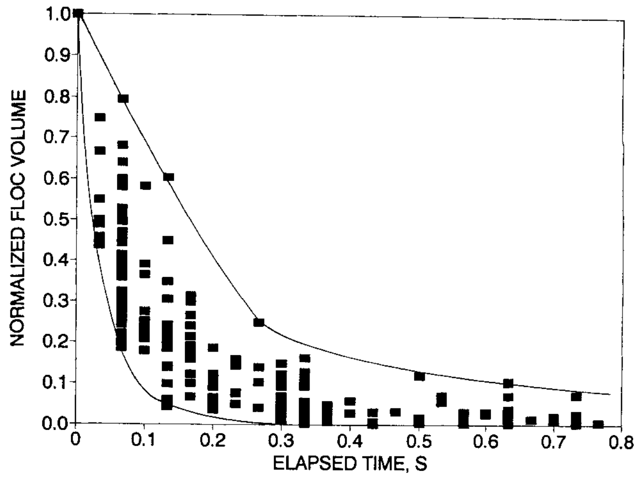

Figure 3. Loss rate of aggregate volume during disintegration at 0.033 s intervals.

were apparent both above and below the mesh and the flow field was decidedly sinuous.

Forward-scatter laser-Doppler velocimetry was also used to characterize flow in the apparatus, both above and below the stainless steel mesh at volumetric flow rates ranging from about 10 to 130 cm^3/s. Low flow rates, e.g., 14 cm^3/s, produced extremely flat distributions. The mean velocity through the screen based on this volumetric flow rate was 2.18 cm/s; by foward scatter LDV, $\bar{v}=2.00$ cm/s at the (centered) measurement location.

The LDV investigation revealed the rms velocity to be highly correlated with the volumetric flow rate Q regardless of vertical position with respect to the screen. In fact, the equation

$$\sqrt{\overline{u}^2}=0.0586Q^{0.947} \tag{1}$$

fits the experimental data within 10% for all Q between 10 and 90 cm^3/s. If the integral length scale does not change significantly with the flow rate, then the dissipation rate per unit mass should vary in the middle of the stainless steel mesh as

$$\bar{\epsilon}\simeq 2\times 10^{-4}Q^{2.84} \tag{2}$$

The relative intensities measured in this phase of the investigation ranged from 35% at Q = 14 cm^3/s to 56% at 125 cm^3/s, making it clear that even for the highly ordered flows studied photographically with $Re \lesssim 1{,}000$, the flow in the vicinity of the mesh was subject to significant velocity fluctuations.

Experimental Results

An extensive set of experiments was conducted as described previously in which kaolin-polymer flocs, restrained by the stainless steel mesh, were subjected to steady flow through the test apparatus. Their behavior under stress was recorded with the video camera, and those images were analyzed manually for particle size, local fluid velocity and severity of breakage. More than 225 individual events were examined in this manner, and a boundary between disintegration and survival was developed. These data are presented in Figure 2; based on our observations, the breakage threshold at a floc diameter of 2 mm is approximately 0.3 dyne. The boundary between disintegration and survival is described by the empirical relation:

$$F_B \simeq 0.0703d^{1.94} \tag{3}$$

where the floc diameter d is in mm and F_B in dynes.

We also developed an experimental procedure in which large kaolin-polymer flocs, at rest upon the stainless steel mesh, were subjected to the initiation of flow in the apparatus. A fixed, constant head arrangement was employed that produced a steady-state flow rate of 196 cm^3/s, corresponding to a Reynolds number of about 8,600; we estimated that the transient period required for flow development was approximately 100 ms. The Canon E640 8-mm video camera, using a shutter speed of 250 or 500 1/s, recorded the disintegration process, which could be reviewed later (frame by frame) at time intervals of 0.033 s. The response of these large and strong flocs to flow initiation was intriguing; usually the first video still following initiation of flow indicated subsidence or compression of the aggregate structure with respect to the flow direction. Often such flocs would elongate with respect to their major horizontal axes and rapidly begin to lose peripheral portions of their structure. The disintegration process appears to be erosive in character in real time, but single frame advance of the video tape shows clearly that the fragments disappearing from the edges of the structure are not primary particles.

The video data were converted to records of aggregate volume with time so that the dynamic process of disintegration could be better characterized. The data obtained form a breakage process envelope partly delineated by the initial values of $-dV/dt$: about 10 to 1,000 mm^3/s. The dynamic nature of this process is clearly illustrated by Figure 3; the disintegration process itself usually occurred over a period of 0.1 to 0.4 s. A number of interacting factors are responsible for the broad range covered by these data, including flocs of common size but widely varying strength due to their level of aggregation and history of formation, and differences in the actual mechanism by which the deaggregation occurred.

In many cases, a skeleton structure survived the breakage process and it seems likely that such instances were the result of very extensive interparticle bridging by macromolecules. Since a batch floc formation procedure was employed with single polymer addition, it is likely that these small, resistant structures were formed very early in the flocculation process while polymer extension was common and multiple bridges could be formed between adjacent particles.

Summary and Conclusions

Experimental procedures have been developed for investigation of floc breakage occurring in response to the hydrodynamic stress. Aggregates initially restrained by a stainless steel mesh were exposed to downward-directed flow, and the subsequent events including deformation and breakage severity were observed. This study provided a video record of the disintegration process under both steady-flow and start-up conditions, yielding both a breakage envelope and a temporal record of loss of aggregate volume during breakage. We prefer to consider these data in terms of the initial change rate in volume of the disintegrating aggregates. As indicated previously, we find that initial values for $(-dV/dt)$ range from about 10 to 1,000 mm^3/s; the broad variation is due to a number of factors, including the level of aggregation of the floc, the floc's strength characteristics, and the hydrodynamic environment at the initial floc position.

An extensive video record of floc breakage events occurring on a support stainless steel mesh has been obtained, providing new insight into the nature of the disintegration process, and the steady-flow experiments have resulted in the delineation of a floc breakage envelope and a qualitative portrait of breakage event severity. In virtually every observation, the floc disintegration process was initiated by vertical compression of the aggregate structure. This was often followed by the shear-induced removal of weakly bound fragments from the periphery.

Acknowledgment

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Notation

d = particle or floc diameter, mm or cm
F_B = force required for floc breakage, dynes
Q = volumetric flow rate, cm^3/s
Re = Reynolds number, dimensionless
S = floc strength parameter, dyne
t = time, s
$\overline{u_-^2}$ = mean-square velocity fluctuation, cm^2/s^2
v = mean velocity, cm/s
V = total floc (particle) volume, mm^3

Greek letters

$\bar{\epsilon}$ = mean dissipation rate per unit mass, cm^2/s^3
τ_y = yield stress, $dyne/cm^2$

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