Floc Sizing Techniques

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ABSTRACT

In the study of mass transfer of substrate through floc particles, it is essential to have an estimate of floc size. This study presents floc size measurements made on pure culture bacterial floc and shows their applicability to mass transfer studies. A critical review of the biological literature on methods to size biological floc and determine wet floc density is also presented.

At present, the activated sludge process is widely used for the treatment of waste waters. The principal purifying agents involved in this process are the bacterial floc particles which stabilize the organic matter in the presence of oxygen. In the study of mass transfer of substrate or oxygen through floc particles, it is essential to have an estimate of floc size.

One method of floc size measurement was described by Schroepfer et al. (6) in 1955. A drop of digester waste from an anaerobic contact process was dispersed in a salt solution and photographed. Using the photographic prints, they measured the maximal dimension of each particle. Morand (Ph.D. Thesis, Univ. Wisconsin, Madison, 1964) measured pure culture floc dimensions by solidifying the floc sample with 3% agar in a petri dish. The floc lengths and breadths were then measured with an ocular micrometer and stereomicroscope. Finstein (personal communication and Bacteriol. Proc., p. 13, 1965) related the total length of filamentous microorganisms associated with activated sludge floc to the diameters of the floc. He dried a dilution of activated sludge on microscope slides, projected the slides on a screen, and traced the outlines of the flocs. Mean floc diameters were obtained by measuring the two extreme points in a horizontal direction.

These methods are basically the same in that they measure only one or two dimensions of the floc particles. With the measurement of only one dimension, the floc length, it is impossible to define the diffusional path in the floc. Measuring the breadths of the floc particles should give a better estimate of the diffusional path, but for irregularly shaped floc an average breadth is difficult to define.

Aiba et al. (1, 2), in 1964, obtained the equivalent diameters of activated sludge floc by measuring the interface settling characteristics of the sludge in a 1-liter graduated cylinder. However, the wet density of the floc was obtained by using an arbitrary settling time of 24 hr. Also, if flocculation took place during the experiment, it would cause erroneous results. With this method, there was a large variation in equivalent diameters among samples obtained from a single treatment plant.

Mueller et al. (4) recently described a method to give the maximal possible diffusional dimension of a floc, the nominal diameter. This method measures the wet volume of a floc, and, by assuming a sphere, the diameter of a floc may be computed. This method yields reproducible results but does not measure the actual diffusional path through the floc.

The latter two methods to determine floc size require an estimate of the wet floc density. The measurement of the wet density of porous solid materials such as biological floc is extremely difficult. Wet density may include water in any or all of the following ways: (i) water adsorbed on the surface, (ii) interstitial water or water absorbed within the floc that retains all colligative properties of water, and (iii) bound water or water bound by colloid micelles with entirely different properties.

Schroepfer et al. (6) used the particle dimensions and velocity of subsidence in a salt solution to compute the wet density of digested waste solids from Stoke's law. Even though the Reynolds' number was greater than 0.6, being 100 to 200, the error involved when Stoke's law was used was only 10 to 20%, since the particle diameters were close to 1 mm. In measuring settling velocities, mass transfer of water out of the floc or of salt into the floc will influence the
rates. This effect will be pronounced in small particle systems such as those encountered with biological flocs. In another method, Schroepper and Ziemke (7) placed sludge particles in a salt solution. The density of that solution which just suspended the sludge particle was taken as the wet density of the particle. In these methods, no attempt was made to distinguish among the types of water present.

Aiba et al. (1) described a method to determine the wet density of cells. In this method, they used the following equation to calculate wet density:

$$\rho_w = \rho_c - (1 - c)\rho_m$$  \hspace{1cm} (1)

where $\rho_w = \text{wet density of the cells (g/cc)}$, $\rho_c = \text{density of the suspension (g/cc)}$, $\rho_m = \text{density of the medium (g/cc)}$, and $c = \text{volume fraction of cells in the suspension.}$

These authors state, "Although the values of $\rho_c$ and $\rho_m$ can be determined accurately for each case with picnometers, the exact determination of $c$ is more difficult. No standard procedure has yet been established to determine the values of $c$ for cell suspensions, and so methods differ from case to case. Cell material is liable to deform under pressure, especially in the case of mycelia, and it is evident that the value of $c$ for fungi cannot be determined by measuring the volume fraction of the sediment obtained after centrifuging, although this method would be satisfactory for bacteria.

"By the same token, it is not permissible to estimate the value of $c$ from the dry weight of suspended particles, since many particles, especially those of multicellular organisms or activated sludge, have a certain amount of liquid associated with them and the whole behaves as an aggregate within the suspension."

To determine the value of $c$ for yeast cells, Aiba et al. (2) centrifuged the suspension at about 700 \times g for 10 min; the ratio of the sediment volume to that of the original suspension gave the value of $c$. In their experiments with activated sludge, the volume of the sediment after 24 hr of settling in a 1,000-ml graduated cylinder was arbitrarily chosen to define $c$. With this method, there is no determination of the amount of water entrapped in the sediment outside the cells or floc particles. It is probably much less when the sample is centrifuged than when it is settled.

To make this measurement less arbitrary, methods have been devised by various investigators to measure the amount of water in the intracellular spaces between the cells in a sediment (5, 8, 9). Basically, these methods consisted of adding the cell suspension to a volume of water containing a tracer substance. This tracer should not be able to diffuse through the cell membranes or be metabolized by the cells. The suspension was then centrifuged, and the sediment or pellet was then analyzed for tracer. Since the concentration of tracer in the intracellular water is the same as in the original suspension, the weight of tracer in the pellet was directly related to the quantity of water in the intracellular spaces. Ross and Mokotoff (5) in 1951 used inulin as a tracer substance. But Wetherell and Pollack (9) found this "inulin space" method unsatisfactory because of the large amount of interfering substances present. They found that polyvinylpyrrolidone was a suitable indicator for the determination of intercellular space in algal suspensions. A magnetic method to determine volume fraction was used by Sugimura and Koga (8). This method, with a paramagnetic ion as a tracer, was applied to yeast cells. The authors found that this method did not measure the total volume of yeast cells but only the volume enclosed in the cell membranes. It seems likely that the other tracers would give the same results. These methods would therefore not be applicable to biological floc, since a substantial portion of the floc volume may be located outside the cell membranes of the organisms.

Mueller et al. (4) used the following method to measure the wet density of activated sludge floc. A sample of activated sludge was centrifuged and a portion of the pellet was air-dried on filter paper until it had sufficient cohesion to be formed into small spheres. The spheres were placed below the surface of potassium bromide solutions of different specific gravities to avoid suspension due to surface tension. If the sphere did not settle immediately, it was considered to have a density equal to or less than the solution density. It was found that the time of air-drying within 0.5 hr after centrifugation had no significant effect on the wet density. Presumably, this method included both interstitial and bound water.

**Materials and Methods**

In the present investigation, the following methods were used to describe the size of a pure culture floc of *Zoogloea ramigera*, strain I-16-M (3), isolated from the activated sludge process.

Specific surface measurement. For any study of mass transfer through floc, it is necessary to know the surface area and volume of the floc as a function of diffusional distance. Lacking this information for irregularly shaped floc, the system can best be defined by the specific surface of the floc—the ratio of the surface...
area to the volume of floc. The diffusional path through the floc is then a direct function of the reciprocal of the specific surface. To define the diffusional dimension from the specific surface, a regular shape for the floc must still be assumed. However, with the specific surface well defined, this assumption does not markedly affect the analysis of the mass transfer characteristics of the floc, as shown by Mueller (Ph.D. Thesis, Univ. Wisconsin, Madison, 1964).

To obtain the specific surface of the I-16-M floc, photomicrographs of the floc were enlarged to 4 by 5 inches. A planimeter and map measurer were used to trace the outlines of the flocs. After multiplication by the proper calibration factors, the planimeter readings measured the cross-sectional area, the total cross-sectional area of the floc particles, and the map measurer readings measured the circumference, . Assuming that the flocs were flat plates, the average thickness of the floc particles, , would be

\[ t = \frac{V}{\bar{S}} \]  

where is the average wet volume and \( \bar{S} \) is the average floc cross-sectional area. The average total surface area of the floc particles is calculated by

\[ S_t = 2\bar{S} + \bar{p} \]  

where \( S_t \) is the average total surface area and \( \bar{p} \) is the average floc circumference. The specific surface of the floc particles is then given by

\[ A_v = \frac{1}{\lambda} = \frac{S_t}{V} \]  

where \( A_v \) is the average specific surface and \( \lambda \) is a direct function of the diffusional path through the floc.

**Nominal diameter measurement.** A measure of the nominal diameter of a floc particle, as described by Mueller et al. (4), is based on the determination of the wet volume of a floc and the assumption that the floc is spherical. (See Appendix for derivation of wet volume expression.) Since a sphere gives a lower specific surface than any other regular shape, the nominal diameter will define the maximal diffusional distance through any given volume.

The wet volumes and nominal diameters of the I-16-M floc particles were calculated by the following equations:

\[ V = \frac{(\rho_d - \rho_m)}{(\rho_w - \rho_m)\rho_d} \frac{SS}{\lambda} \times 10^{-3} \]  

where is the average wet floc volume (mm\(^3\)/floc), \( \rho_d \) = dry density of floc (g/cc), \( \rho_w \) = wet density of floc (g/cc), \( \rho_m \) = density of the medium (g/cc), \( SS \) = suspended solids (dry floc weight) per unit of fluid volume (mg/liter), and \( N \) = number of floc per unit of fluid volume (number of floc/ml).

\[ d_n = \left[ 1.91 \times 10^6 \frac{(\rho_d - \rho_m)SS}{(\rho_w - \rho_m)\rho_d N} \right]^{1/8} \]  

where \( d_n \) is the nominal diameter of the floc particles in microns.

**Microscopic sizing.** The I-16-M floc particles were observed microscopically, and the mean lengths, breadths, and widths of any protrusions or arms were measured. The method used was similar to that described by Morand (Ph.D. Thesis, Univ. Wisconsin, Madison, 1964). The floc particles were solidified in agar and sized with an ocular micrometer and stereomicroscope at 15 times magnification.

**Wet density of floc.** The method used in this research to obtain wet density was similar to that of Mueller et al. (4). However, to eliminate almost completely any mass transfer effect, the salt solutions used in the density determinations were replaced by solutions containing different concentrations of carbon tetrachloride and xylol. Since water is immiscible in these solutions, any mass transfer would be extremely slow. The centrifuge time to concentrate the floc was 1 min at a speed to give a force about 700 \( \times \) g.

**Dry density of floc.** The dry density determination was made with the pycnometer method used by Schroepfer et al. (6). About 20 flasks, containing I-16-M floc which had been grown on a shaker, were concentrated and washed twice with distilled water. The concentrated floc was then centrifuged in a 15-ml centrifuge tube for 1 min at a force about 700 \( \times \) g. This tube, along with a flask of distilled water, was placed in a water bath in a controlled temperature room at 30 C.

After temperature equilibrium was reached, the distilled water sample (medium) was pipetted into a 10-ml pycnometer. The stopper was carefully placed into the pycnometer so as not to entrap air bubbles, and the surface of the pycnometer was dried with tissue paper. The capillary tube in the stopper was dabbed with tissue paper until the medium was down to a specific mark. The pycnometer was then weighed. This procedure was repeated with five samples of distilled water to establish the variation in the method. A wide-mouth pipette was then used to transfer the floc sample into the same pycnometer used for the preceding measurements. The pycnometer containing the floc was filled with distilled water, and the above procedure was again followed. After weighing, a suspended solids analysis was made on the pycnometer contents.

The following equation was used for the calculation of the dry density:

\[ d = \frac{\rho_m}{1 - \frac{\Delta W}{SS}} \]  

where \( \rho_d \) = the dry density of the floc (g/cc), \( \rho_m \) = the density of the distilled water (g/cc), \( \Delta W \) = the difference in weight between the pycnometer containing medium plus floc and the pycnometer containing only medium (mg), and \( SS \) = the suspended solids of the floc in the pycnometer (mg).

After the determination of the wet and dry densities, the amount of water in the floc can be calculated from

\[ P_w = \frac{10^{6} \left( \frac{\rho_d - 1}{\rho_m} \right)}{P_w} \]  

where \( P_w \) is the percentage of water in the floc.
Suspended solids determination. All suspended solids determinations were made with a filter apparatus employing a 0.45 micron pore size filter (no. HAWP 047 A O; Millipore Filter Corp., Bedford, Mass.). A control and test filter were used to take into account the loss of weight of the filter during drying. Before taking the initial weights of the filters, they were preheated for 1 hr in an oven at 103°C and then were desiccated.

Floc numbers determination. A flask containing the floc particles was mixed with a magnetic mixer, and three 5-ml and three 10-ml samples were withdrawn with wide-mouth pipettes. These samples were added to petri dishes, and agar (2.5%), which had been cooled to about 50°C, was poured into the dishes to suspend the floc as outlined by Morand (Ph.D. Thesis, Univ. Wisconsin, Madison, 1964). The floc particles in each of these plates were counted with a Quebec counter. The average of these counts, after being multiplied by the proper dilution factor, was assumed to represent the number of floc per milliliter of reactor volume, and was used in the nominal diameter determinations.

Growth conditions. Pure cultures of Z. ramigera I-16-M were stored on a 1.5% agar-3.0% Trypticase Soy Broth (BBL) slant at 5°C. For an experiment, a loopful of this culture was transferred to another slant and incubated at 30°C for 24 hr. Growth from this slant was subsequently transferred to four other slants which were incubated at 30°C for 24 hr. The growth was washed from these slants with 5 ml of sterile medium and pipetted into a flask containing approximately 200 ml of medium. The floc was dispersed with a Waring Microblendor for 2 min (Morand, Ph.D. Thesis, Univ. Wisconsin, Madison, 1964). The optical density of this suspension at 650 μm was adjusted to 0.2 by addition of medium, and dispersed cells were added to flasks in the proportion of 2 ml of inoculum to 98 ml of medium, giving a viable count in the flasks of approximately 10⁶ cells per milliliter.

The medium used throughout this study had the following composition: glucose, 0.50%; NH₄NO₃, 0.057%; MgSO₄, 0.020%; KH₂PO₄, 0.050%; K₂HPO₄, 0.10%; FeCl₃, trace; cyanocobalamine (B₁₂), 20 μg/ml. The organisms were grown in 300-ml, unbaffled, Delong culture flasks with Morton stainless-steel closures. Flasks were agitated with a model G-25 New Brunswick Scientific gyrorotory shaker at 160 rev/min. Preliminary studies indicated that different agitation rates and, therefore, different floc sizes could be obtained by varying the volume of media in the flasks. Three volumes, 200, 150, and 100 ml, were used in these investigations.

RESULTS

Floc densities. The wet densities of the floc particles obtained for each experiment ranged from 1.08 to 1.10 g/cc with the major portion of the values at 1.09 g/cc. The plot of air-drying time versus density (Fig. 1) exhibits a plateau at a density of 1.09 g/cc. This plateau was assumed to indicate the wet density of the floc when it contained only absorbed or interstitial water and bound water. Before the plateau, the change in floc density is slow. This is assumed to represent the loss of both interstitial and bound water from the floc particles. The results of this investigation indicated no change of wet density with age (incubation time) or temperature. Therefore, the wet density of the I-16-M floc was assumed to be 1.09 g/cc under all growth conditions.

As with wet density, dry density showed no marked trend with age or temperature. Therefore,
the mean dry density for the I-16-M floc of 1.29 g/cc, with a standard deviation of ± 0.028 g/cc, was used in the floc size estimates.

By use of a wet density of 1.09 g/cc and a dry density of 1.29 g/cc, the percentage of water in the floc can be calculated (equation 8) as 63%. For activated sludge, Mueller et al. (4) found wet densities to vary from 1.04 to 1.10 g/cc, dry densities from 1.38 to 1.65 g/cc, and values for percentage of water in the floc from 73 to 90% with an average of 80%. The greater dry density and, consequently, percentage of water of the activated sludge floc as compared with the I-16-M floc is probably caused by inclusion of grit particles and other inert suspended matter in the activated sludge floc.

**Floc sizing results.** The nominal diameter, \(d_n\), and the reciprocal of the specific surface, \(\lambda\), at 30 C are plotted in Fig. 2 as a function of age. It is apparent that the nominal diameters at both agitation rates, as measured by the different volumes of medium in the flasks, increased with increasing age of the organisms. Contrary to the above results, the values for the reciprocal of the specific surface do not appear to increase with age.

Photomicrographs of the floc grown at 30 C are presented in Fig. 3 for the lower agitation rate and in Fig. 4 for the higher agitation rate. Since there was an actual size distribution of floc particles at each age, as shown in Fig. 8, the floc particles depicted in the following figures were chosen as representative of the average floc size at each age. Note that the floc particles at the higher agitation rates are generally smaller than those at the lower rate.

At a growth temperature of 20 C, a trend similar to that at 30 C was noted.

**Relationship among floc sizes obtained by different methods.** Figure 5 depicts the relationship between nominal diameter and specific surface as measured by the specific spherical diameter. This specific spherical diameter is defined as the diameter of a sphere with a surface area to volume ratio equal to the measured specific surface; therefore, \(d_s = \sqrt{6} \cdot \lambda\). This differs from the nominal diameter, which also assumes a sphere, since the nominal diameter is based solely on the volume of the floc. One may deduce from this figure that the nominal diameter tends to increase more rapidly than the specific spherical diameter.

The larger nominal diameters are about five times greater than the specific spherical diameters. But the smaller nominal diameters are only about twice as great as the specific spherical diameters. This trend leads one to the conclusion that the floc becomes more spherical when it decreases in size. This conclusion agrees with the observations made from the photographs that the smaller floc have a more regular shape than the larger ones (Fig. 3, 4, 6).

Figure 7 is a plot of the nominal diameter of the floc versus the average length of the floc, average width of the floc, and the average width of the floc arms obtained by microscopic sizing of the floc. This figure illustrates that all the dimensions of the floc increased with increasing nominal diameter. The average lengths of the floc particles were three to four times greater than the nominal diameters. The average widths were about equal to the nominal diameters, whereas

![Fig. 2. Plot of nominal diameter and reciprocal of specific surface versus age at 30 C.](http://aem.asm.org/ on January 9, 2021 by guest)
the average widths of the floc arms were generally less than one-half the nominal diameters. Thus, the nominal diameter seems to represent the average width of the floc, and the specific spherical surface, since it is less than one-half the nominal diameter, seems to represent a dimension equivalent to or smaller than the floc arms.

**Floc size distribution.** As mentioned previously, a distribution of floc sizes was observed in each experiment. An estimate of this distribution could be obtained from the specific surface measurements, since the floc, obtained from a uniform sample taken from the reactor, were sized individually. The distribution of floc cross-sectional areas and circumferences seemed to be log normal. As a typical example, the distribution of these parameters for a typical experiment is depicted in Fig. 8. These observations agree with those of Morand (Ph.D. Thesis, Univ. Wisconsin, Madison, 1964), who determined that the microscopic floc lengths were also log normally distributed. Figure 9 illustrates the relationship between cross-sectional area and circumference for a typical experiment. As would be expected, the

**Fig. 3.** Photomicrographs of floc grown at 30 C in 200 ml of medium. × 68. Ages: top, 24 hr; middle, 48 hr; bottom, 72 hr.

**Fig. 4.** Photomicrographs of floc grown at 30 C in 150 ml of medium. × 70. Ages: top, 24 hr; middle, 48 hr; bottom, 72 hr.
FIG. 5. Relation between nominal diameter and specific spherical diameter.

FIG. 6. Photomicrographs of floc grown at 20°C in 100 ml of medium. ×175. Ages: top left, 24 hr; top right, 48 hr; bottom left, 72 hr; bottom right, 96 hr.
floc circumference increases with increasing cross-sectional area.

The mean floc parameters obtained by specific surface measurements are tabulated in Table 1. The number of floc particles measured in each experiment varied from 21 to 45. This number was sufficient to yield a standard deviation of the mean which was always less than 16% and usually less than 10% of the mean floc parameters. It must be emphasized that the distributions obtained in this study represent the distribution of only the floc cross-sectional area and circumference. The distribution of the floc specific surfaces was not determined, since the distribution of the floc volumes could not be measured by the method employed to measure floc volume.

Table 2 presents a summary of the methods of sizing biological floc given in the literature and used in this study. Examination of these methods indicates that the best floc-sizing method for mass transfer studies is the specific surface

**TABLE 1. Summary of floc cross-sectional areas and circumferences**

<table>
<thead>
<tr>
<th>Expt</th>
<th>No. of observations</th>
<th>Mean cross-sectional area, mm²</th>
<th>Standard deviation of mean</th>
<th>Mean cross-sectional circumference, mm</th>
<th>Standard deviation of mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>29</td>
<td>0.120 ±0.009</td>
<td>2.99 ±0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>0.188 ±0.016</td>
<td>4.49 ±0.31</td>
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<td></td>
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<tr>
<td>10</td>
<td>21</td>
<td>0.353 ±0.037</td>
<td>5.86 ±0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>38</td>
<td>0.304 ±0.043</td>
<td>4.74 ±0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>44</td>
<td>0.066 ±0.006</td>
<td>1.94 ±0.13</td>
<td></td>
<td></td>
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<tr>
<td>13</td>
<td>35</td>
<td>0.145 ±0.015</td>
<td>3.33 ±0.29</td>
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<tr>
<td>14</td>
<td>40</td>
<td>0.157 ±0.016</td>
<td>3.47 ±0.32</td>
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<tr>
<td>15</td>
<td>41</td>
<td>0.175 ±0.014</td>
<td>3.63 ±0.27</td>
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<tr>
<td>16</td>
<td>41</td>
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<td>6.72 ±0.45</td>
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<tr>
<td>17</td>
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<td>0.335 ±0.043</td>
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<tr>
<td>18</td>
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<td>0.081 ±0.008</td>
<td>1.87 ±0.16</td>
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<tr>
<td>19</td>
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<td>2.51 ±0.22</td>
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<tr>
<td>20</td>
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<td>21</td>
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<td>22</td>
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<td>0.185 ±0.018</td>
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<tr>
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<td>31</td>
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<tr>
<td>30</td>
<td>36</td>
<td>0.043 ±0.004</td>
<td>0.97 ±0.06</td>
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<tr>
<td>31</td>
<td>37</td>
<td>0.044 ±0.007</td>
<td>0.86 ±0.07</td>
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</table>

**FIG. 7. Relation between nominal diameter and microscopic sizes.**

**FIG. 8. Distribution of floc cross-sectional areas and circumferences for experiment 9.**
<table>
<thead>
<tr>
<th>Method</th>
<th>Procedure</th>
<th>Floc sample</th>
<th>Sizes obtained</th>
<th>Reference</th>
<th>Applicability to mass transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific surface</td>
<td>Estimate of floc surface area from floc photographs and wet volume</td>
<td>Zoogloea ramigera</td>
<td>Specific spherical diameters, 31–68 μ</td>
<td>This study</td>
<td>Good estimate of actual diffusional dimension. Gives a distribution of floc cross-sectional areas and circumferences.</td>
</tr>
<tr>
<td>Nominal diameter</td>
<td>Analytical determination of wet volume; assumes a spherical floc</td>
<td>Activated sludge</td>
<td>21–115 μ</td>
<td>Mueller et al. (4)</td>
<td>Yields maximal possible diffusional path in the floc. Gives no distribution of diffusional distances.</td>
</tr>
<tr>
<td>Equivalent diameter</td>
<td>Measures interface settling characteristics of sludge.</td>
<td>Activated sludge</td>
<td>79–250 μ</td>
<td>This study</td>
<td>Wet volume of floc determined from an arbitrary settling time. Wide variation of results for one plant. Gives no distribution of diffusional distances.</td>
</tr>
<tr>
<td>Microscopic sizes</td>
<td>Microscopic measurement of average floc lengths, widths, and arm widths</td>
<td>Zoogloea ramigera</td>
<td>Lengths, 385–1,150 μ; widths, 100–260 μ; arms, 50–175 μ</td>
<td>This study</td>
<td>Since floc particles are irregular in shape, it is difficult and tedious to obtain meaningful floc dimensions. It is impossible to describe irregular-shaped floc with only one dimension. If floc are not spherical, measured length is greater than maximal possible diffusional path. Gives floc size distribution.</td>
</tr>
<tr>
<td>Photographic sizes</td>
<td>Photographic measurement of maximal particle dimension</td>
<td>Anaerobic digester</td>
<td>Lengths, 260–530 μ; 100–4,500 μ</td>
<td>Morandb</td>
<td></td>
</tr>
<tr>
<td>Image projection</td>
<td>Scaling of maximal horizontal dimensions of dried sample from projection of image</td>
<td>Activated sludge</td>
<td>20–200 μ</td>
<td>Finsteinb</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 9. Relation between cross-sectional area and circumference of cross section for experiment 9.

method. It gives the best estimate of the average diffusional dimension of the floc, since it is calculated from both the wet volume of the floc and the surface area of the floc. By assuming a shape for the floc particles, e.g., spherical, as is done in Table 2, the average diffusional path can be calculated for the particles. The nominal diameters obtained in this study represent the maximal possible diffusional dimension and were about two to five times greater than the specific spherical diameters.

APPENDIX

Derivation of Wet Volume Expression (Equation 5)

We may assume that the wet floc density is the resultant of two components, the dry floc density and the floc-associated media density as follows:

\[ \rho_w = \rho_d Y + \rho_m (1-Y) \]  \hspace{1cm} (9)

where

\[ Y = \frac{V_d}{V} \]  \hspace{1cm} (10)

and \( \rho_w \) = wet density of floc (g/cc), \( \rho_d \) = dry density of floc (g/cc), \( \rho_m \) = density of the medium (g/cc), \( V_d \) = dry volume of floc (mm³), and \( V \) = wet volume of floc (mm³). Thus, solving for \( Y \)

\[ Y = \frac{\rho_w - \rho_m}{\rho_d - \rho_m} \]  \hspace{1cm} (11)

and, substituting equation 11 into equation 10 and solving for \( V \), we obtain:

\[ V = \frac{\rho_d - \rho_m}{\rho_w - \rho_m} V_d \]  \hspace{1cm} (12)

To obtain an average volume per floc, the number of floc per milliliter of media are counted, \( N \), and a dry volume per floc may be calculated from a dry solids determination as follows:

\[ V_d = \frac{SS}{\rho_d N} \times 10^{-3} = \frac{V_d}{N} \]  \hspace{1cm} (13)

Dividing equation 12 through by \( N \) and substituting equation 13, we obtain equation 5:

\[ V = \frac{(\rho_d - \rho_m) SS}{(\rho_w - \rho_m) \rho_d N} \times 10^{-3} \]

where \( V \) and \( V_d \) are, respectively, the wet and dry volumes per floc (mm³/floc).

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LITERATURE CITED


