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Shear schedule determination method using image analysis of flocculation processes

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ABSTRACT

This study proposes a batch test procedure for the determination of shear schedules in conventional flocculation processes consisting of three successive flocculation basins. The determination is based on variations in the average floc size, indicating floc growth or breakage. The trends in the floc sizes with varying shear schedules are in good agreement with those of the residual turbidity. It is found that formation of large flocs is important for maintaining their large size in subsequent stages, given an appropriate selection of the shear strength. This suggests that shear strength should be selected on the basis of floc size. The suggested testing procedure offers a range of effective shear schedules, and the optimum shear schedule can be selected based on the requirements of subsequent processes or restrictions of the operational conditions.

Keywords: Shear schedule; Floc size; Feret diameter; Flocculation; Tapered mixing; G value

1. Introduction

Conventional solid–liquid separation usually consists of three consecutive flocculation basins followed by a sedimentation basin. Generally, a tapered shear strength based on suggested G values is applied to flocculation processes. However, not only is the recommended range of G values too wide to determine the optimum conditions for a particular water treatment plant [1–3], but once a shear schedule (strength and time) is determined, the coagulant type and dosage are the only operational factors controlled, and depend on the turbidity of the incoming raw water. While most water plants periodically use a simple batch test procedure to determine the optimum coagulant dosage, no such method is available to obtain information on efficient shear schedules. In addition, determining the optimal shear schedule is complicated and time-consuming when using existing batch tests with residual turbidity, as a combined set of three different shear strengths need to be considered.

Flocculation processes are designed to reduce the number of suspended particles present in subsequent treatment processes by forming flocs, and the efficiency of these processes depend greatly on the degree of floc growth [4–6]. Current tapered shear schedules are designed with three flocculation

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stages. This process has a stepwise application of decreasing shear rate to grow flocs continuously and prevent possible floc breakage [1,7,8]. However, in some cases, the actual rate applied to practical processes may not be effective for floc formation and the optimum rate may lie elsewhere.

This study aims to develop a batch test procedure that can determine an effective shear schedule, assuming the presence of three consecutive flocculation basins and a subsequent sedimentation process. In this method, the evaluation of flocculation efficiency is based on the average floc size, with changes in the average size representing floc growth or breakage. The floc size data obtained with an image analysis method were compared with turbidity measurements, which are popular in practice, and this comparison was used to assess the flocculation efficiency determined by this method.

2. Experimental methods

An aqueous suspension of kaolin particles was flocculated in a 1 L jar. The particles had an average size of 4.54 μm, with 98% of the total population measuring less than 10 μm in a Coulter counter analysis. The solid volume fraction was 1.4×10^{-5}, corresponding to a turbidity of 20 NTU. The suspension was mixed by controlled stirring, as shown in Fig. 1. The center of the impeller was positioned at 1/3 the height of the jar. Acetic acid (CH_3COOH) and sodium bicarbonate ($NaHCO_3$) were added to provide an alkalinity of 50 ppm as $CaCO_3$ to the suspension. A 1 mM concentration of sodium bicarbonate was used as a buffer, and the pH was maintained at 7.60 ± 0.05 during all experiments. Aluminum sulfate hydrate ($Al_2(SO_4)_3{\cdot}16H_2O$) at 1% (w/v) was used as a coagulant. The coagulant concentration was 15 ppm, as that concentration resulted in reasonable floc growth in preliminary standard jar tests at constant shear strength. The coagulant was added to the suspension and stirred at 200 s^{-1}. This rapid mixing continued for 30 s to ensure a quick, uniform dispersion of the aluminum sulfate.

The shear strengths in the main test schedule were established assuming that: (1) the practical solid/liquid separation process consists of three consecutive flocculation basins of 127.5 m^3 each, and (2) the flow rate of incoming raw water remains constant at 3.9 m^3/s. Based on these assumptions, the retention time in each flocculation basin was calculated to be 13 min. The mixing periods are called flocculation stage 1 (F.S. 1), flocculation stage 2 (F.S. 2), and flocculation stage 3 (F.S. 3). The shear strength was intentionally changed after F.S. 1 and F.S. 2 to observe the effect of a combination of two successive shear strengths on floc growth. Details of the shear strengths used in these experiments are described in section 3.

Samples of 20 mL of suspension were collected twice in each flocculation stage (at an interval of 390 s) using a pipette with a tip of 10 mm in diameter to prevent possible floc breakage. The sampled suspension was placed in a $2 \times 100 \times 100$ mm^3 Perspex cell for microscopic imaging. Digital images of the flocs (40× magnification) were captured with a digital camera (Coolpix 4500, Nikon, Japan) attached to a microscope (Meiji Techno Co., Japan), and were analyzed to obtain average floc size and floc size distribution data for each sample. The experimental setup is shown in Fig. 1. The Feret diameter was used to represent floc size in this study,

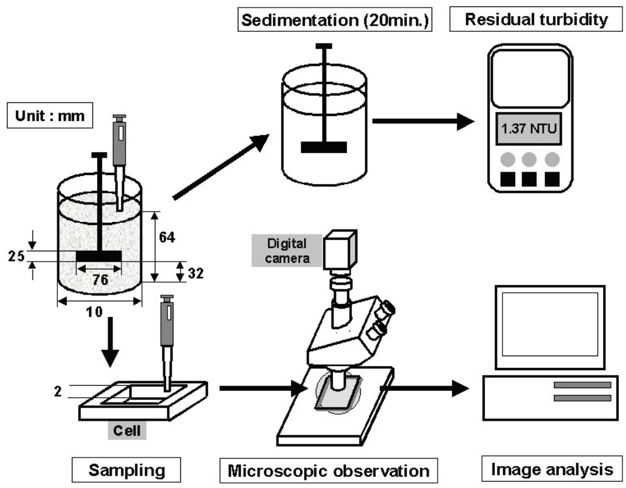

Fig. 1. Schematic illustration of the experimental setup.

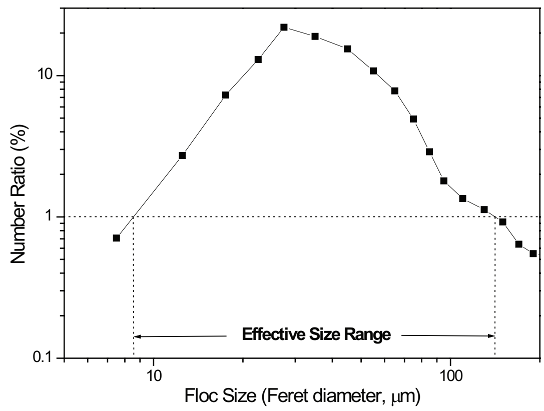

Fig. 2. Floc size distribution observed at a shear strength of 115 s^{-1} that remained constant for 780 s.

and is defined as the average of the longest horizontal and vertical lengths of the particle or floc profile. Approximately 1,200–1,500 flocs were counted for each sample, and most of the observed floc size distributions were in the range of 5–100 μm, as shown in Fig. 2.

Residual turbidity was measured for each flocculation stage with a turbidimeter (2100P, Hach, USA) after the flocculating suspension was allowed to stand for 20 min. The measurement results were then compared with the floc sizes obtained from the imaging method. This comparison of the variations and trends obtained by both methods is intended to evaluate the acceptability of the suggested method, as flocculation efficiency based on residual turbidity is still the standard method in practice in most water plants.

3. Results and discussion

3.1. Determination of shear strength in flocculation stages 1 and 2

Fig. 3 shows the average Feret diameter of the flocs obtained from four sampling points in F.S. 1 and F.S. 2. For F.S. 1, five different shear strengths in the range of 20–170 s^{-1} were applied, while a range of strengths were applied in F.S. 2 to observe further floc growth or breakage.

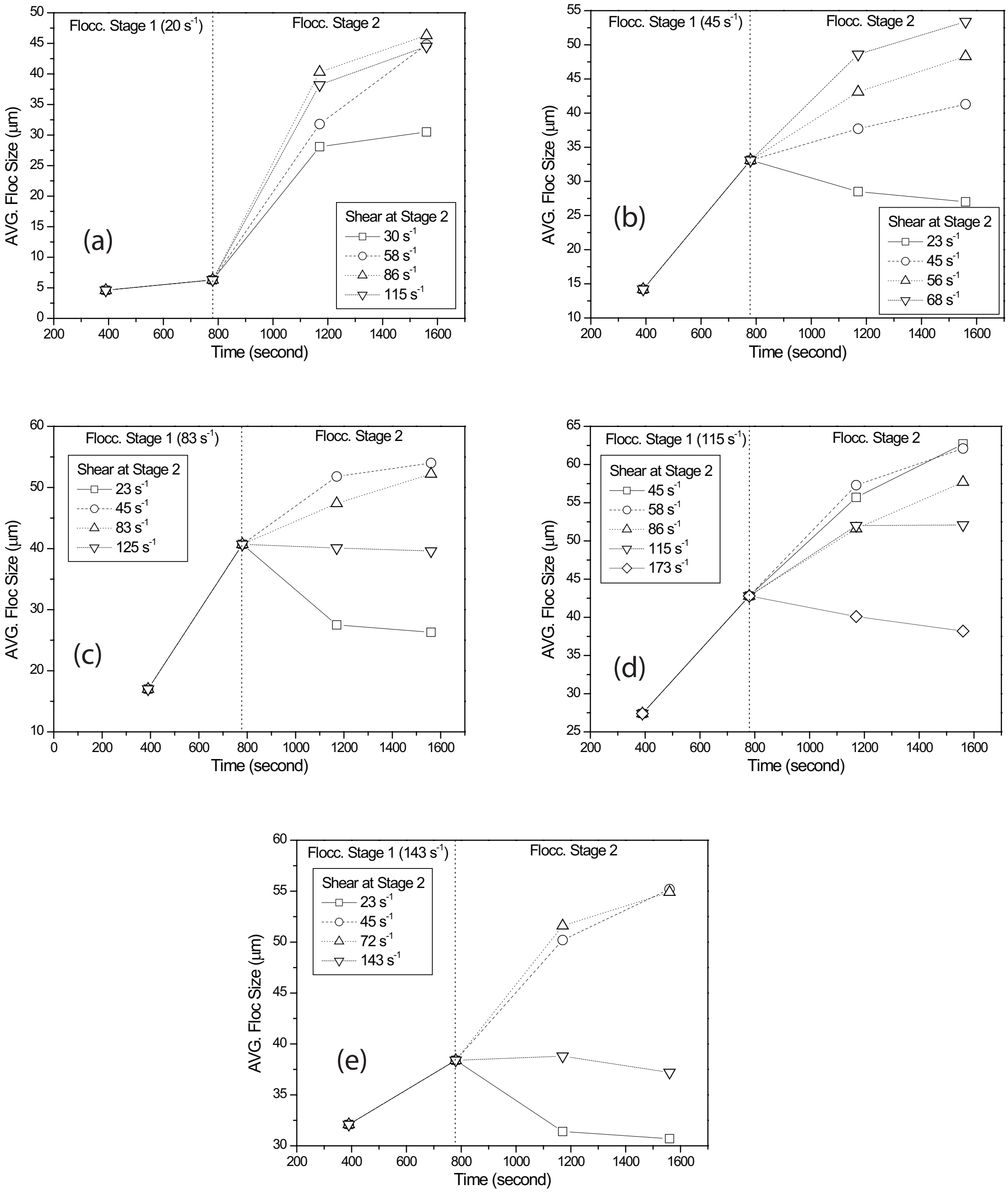

Fig. 3. Floc size changes in flocculation stages 1 and 2, (a) 20 s^{-1} in F.S. 1, (b) 45 s^{-1} in F.S. 1, (c) 83 s^{-1} in F.S. 1, (d) 115 s^{-1} in F.S. 1, (e) 143 s^{-1} in F.S. 1.

These results indicate that the size of the flocs formed in F.S. 1 strongly affects further floc growth in F.S. 2. Formation of large flocs in F.S. 1 leads to the development of the largest possible flocs in F.S. 2, given an appropriate selection of shear strength. The maximum floc sizes for each shear schedule are listed in Table 1, and the results indicate that the formation of large flocs in F.S. 1 continues in F.S. 2. In addition, the shear strength corresponding to the maximum average floc size in F.S. 2 depends on the floc size obtained in F.S. 1. When flocs are small (5–30 μm), increased shear works favorably for floc growth. For large flocs (over 30 μm), decreased shear leads to floc growth while floc breakage occurs with increasing shear strength. For flocs in the size range of 38.4–42.8 μm, a shear strength of 45 s^{-1} leads to efficient further aggregation, while some breakage or very slow floc formation occurs with other strengths in F.S. 2. Based on this trend, it seems that there is a correlation between shear strength and the size of flocs formed at a given shear. Similar observations have been made that floc size depends on energy dissipation [8–11], although that dependence is limited to the maximum floc size.

Table 1 lists the residual turbidities corresponding to the maximum floc sizes. These results demonstrate that an increasing average floc size results in decreasing residual turbidity. It is also noteworthy that even without flocculation in F.S. 2, reasonably low residual turbidities (i.e., large floc sizes) were achieved.

Table 1
Floc size and residual turbidity for efficient shear combinations in flocculation stages 1 and 2

Applied shear at stage 1 and 2 (s^{-1})	Floc size after stage 1 (μm)	Floc size after stage 2 (μm)	Corresponding residual turbidity (NTU)[a]
20–86	6.3	46.3	16–0.95
45–68	33.1	53.4	4.33–0.53
83–45	40.7	54.3	1.02–0.42
115–45	42.8	62.1	0.95–0.36
143–45	38.4	52.2	1.97–0.51

[a]Residual turbidities measured after flocculation stages 1 and 2, respectively.

When a shear strength of 23 s^{-1} was applied in F.S. 2, sedimentation of large formed flocs occurred. This resulted in a failure to capture the large formed flocs during sampling and led to a decrease in the average floc size. Sedimentation of the flocs in the flocculation basin due to generation of very large flocs or low shear strengths should be avoided. As the results of this study demonstrate, this problem can be solved or prevented in practical applications by controlling the shear strength.

3.2. Determination of shear strength in flocculation stage 3

The shear combinations that produced the largest average floc sizes in the previous experiments were used for F.S. 1 and F.S. 2 in these tests. Shear strengths of 30–68 s^{-1} were applied in F.S. 3, and the resulting variations in average floc size are shown in Fig. 4.

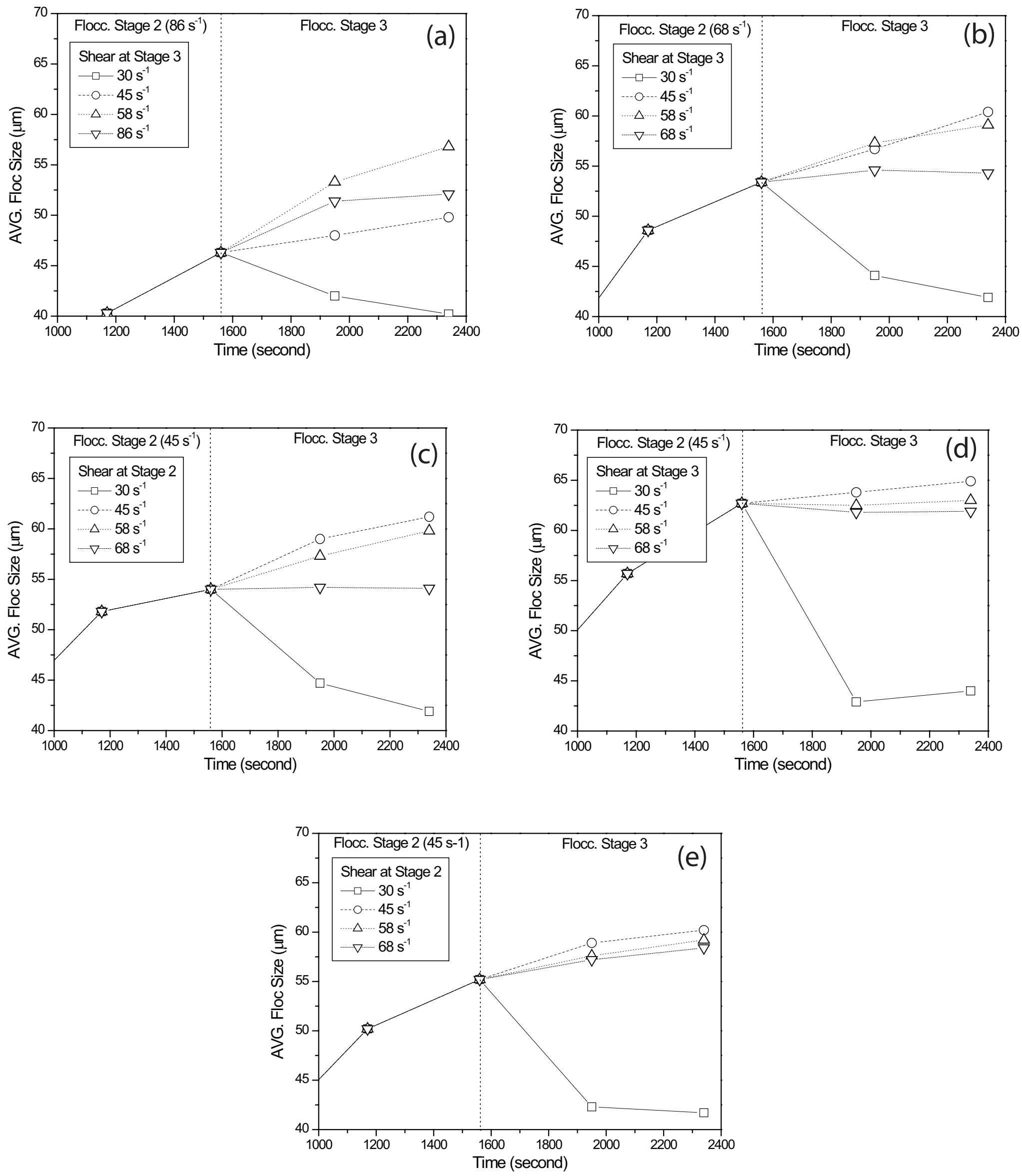

Fig. 4. Floc size changes in flocculation stage 3, (a) 20 s^{-1} in F.S. 1 and 86 s^{-1} in F.S. 2, (b) 45 s^{-1} in F.S. 1 and 68 s^{-1} in F.S. 2, (c) 83 s^{-1} in F.S. 1 and 45 s^{-1} in F.S. 2, (d) 115 s^{-1} in F.S. 1 and 45 s^{-1} in F.S. 2, (e) 143 s^{-1} in F.S. 1 and 45 s^{-1} in F.S. 2.

These results indicate that floc growth occurs in F.S. 3, but it is not as efficient as in the preceding stages. This may be because the flocs have already grown to almost their maximum size by this point. Therefore, decreased shear strength (F.S. 2 of 86 or 68 s^{-1} and F.S. 3 at 30 s^{-1}) or the same shear strength (F.S. 2 and F.S. 3 at 45 s^{-1}) in F.S. 3 maintains further floc growth, although only a slight increase in floc size occurs.

The effect of shear strength on the maximum floc size in F.S. 3 depending on the floc size in F.S. 1 was not observed as it was for F.S. 2, and the most effective shear strength was 45 s^{-1} in all cases. Furthermore, the flocs formed after F.S. 2 are large enough to settle when stirred at the very low shear strength of 30 s^{-1} (represented by an immediate decrease in average floc sizes in Fig. 3), while 45 s^{-1} is the lowest strength that leads to floc growth and still keeps large flocs suspended. These results indicate that the focus in F.S. 3 should be on maintaining the floc sizes formed in F.S. 1 and F.S. 2, rather than promoting further floc growth.

Similar to the results in the previous section, these experiments can provide the appropriate shear strength for the generation of larger flocs in F.S. 3 from the flocs generated in F.S. 2. This provides an opportunity to achieve higher removal efficiencies in subsequent sedimentation processes.

The residual turbidity results for the highest average floc sizes are listed in Table 2. The correlation between turbidity and floc size is not entirely consistent, as indicated by the boldfaced values in Table 2. However, considering experimental errors that occur often with the measurement of very low turbidities, such discrepancies are considered acceptable.

Table 2
Floc size and residual turbidity for the efficient shear combinations in flocculation stages 2 and 3

Applied shear at stage 1, 2 and 3 (s^{-1})	Floc size after stage 2 (μm)	Floc size after stage 3 (μm)	Corresponding residual turbidity (NTU)[a]
20-86-30	46.3	56.8	0.95–0.36
45-68-45	53.4	60.4	0.53–0.30
83-45-45	54.3	**61.2**	0.42–**0.38**
115-45-45	62.1	64.3	0.36–0.29
143-45-45	52.2	**60.2**	0.51–**0.31**

[a]Residual turbidities measured after flocculation stages 2 and 3, respectively.

3.3. Flocculation efficiency based on residual turbidity and average floc size

According to the results of this study, the shear schedules such as the tapered mixing or constant mixing schemes that are currently applied in practical flocculation processes, are not a significant factor for increasing the efficiency of the flocculation process. To achieve increased efficiency, the formation of larger flocs is necessary to obtain lower residual turbidities. To achieve this, it is important to select an appropriate shear strength based on the floc sizes and residual turbidity of the previous stage. When flocculation efficiency is low in F.S. 1, the rate of floc growth is high in F.S. 2 with increased shear, whereas decreased shear should be applied in F.S. 2 if large flocs are formed in F.S. 1. However, the floc growth rate is very low in F.S. 3 in all cases, as summarized in Table 3. Fig. 5 illustrates the contribution of each flocculation stage based on the turbidity removal ratio, and indicates that the trend is similar to the size changes observed in Table 3. According to these results, removal efficiencies of 98% or greater were obtained for all combinations of the five flocculation conditions. Each bar in Fig. 5 indicates the contribution of each stage to the turbidity removal. For example, F.S. 2 had the largest contribution to the turbidity removal for the shear combination of 20-86-30 s^{-1} (F.S. 1-F.S. 2-F.S.-3), whereas F.S. 1 provided the largest contribution to turbidity removal in the other four combinations. In particular, the shear combinations of 83-45-45 and 115-45-45 s^{-1} (F.S. 1-F.S. 2-F.S.-3) had very large contributions from F.S. 1. These results indicate that flocculation basins can be designed in

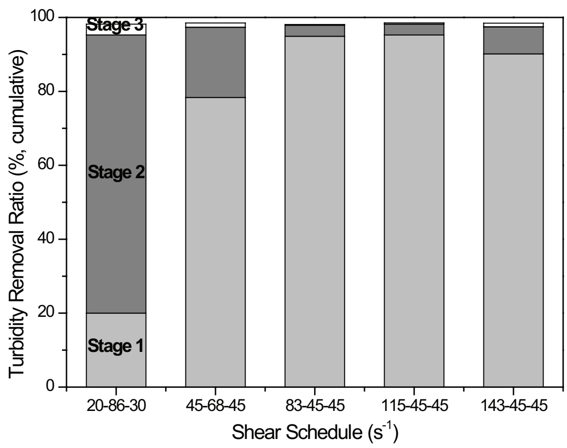

Fig. 5. Turbidity removal ratios for each flocculation stage.

Table 3
Shear strength and average floc size in each flocculation stage

Shear in stage 1 (s^{-1})	Floc size after stage 1 (μm)	Shear in stage 2 (s^{-1})	Floc size after stage 2 (μm)	Shear in stage 3 (s^{-1})	Floc size after stage 3 (μm)
20	6.3	86	46.3	30	56.8
45	33.1	68	53.4	45	60.4
83	40.7	45	54.3	45	61.2
115	**42.8**	**45**	**62.1**	**45**	**64.3**
143	38.4	45	55.2	45	60.2

one or two stages. These results do not completely agree with the existing recommendations and suggest that various shear schedules can be recommended for efficiency. In many currently operating water treatment plants, relatively low shear strength is applied [7,12]. For these conditions, the proposed method proposed indicates that an increased shear schedule is more effective than a tapered shear schedule. In addition, this study demonstrates that it is possible to determine the shear intensity and size of the flocculation basin with economic efficiency.

4. Conclusion

This study suggests a method to determine an effective shear schedule at a batch test scale using variations in the average floc size. Floc size results obtained from a newly developed imaging method compare well with the conventional turbidity measurement method. Furthermore, this imaging method is superior to the residual turbidity measurement, owing to its ability to obtain direct information on floc sizes and conduct more frequent sampling in batch tests. In particular, by applying a variety of calibration methods or an automatic measuring program, large amounts of data can be processed faster and more accurately. Furthermore, if the device can measure the size of the flocs without breakage, it can be applied immediately in practical processes.

For the given 13 min of each flocculation stage, most of the observed floc growth occurs in the first stage. After this stage, average floc size increases to a certain size depending on the specific shear strength. When flocs are formed with an average size of greater than 40 μm, a relatively low shear strength (i.e., 45 s^{-1}) promotes further floc growth. Generally, the size of the flocs formed in the preceding stage has a significant effect on the degree of size increase.

The testing procedure developed in this study enables determination of the optimum shear schedule in practical flocculation processes. The range of shear schedules provided by this testing procedure could be useful for operational conditions such as those restricted to low G values.

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