Continuous tapered flocculation in conical and cylindrical tanks

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The progressive reduction of velocity gradient to keep the flocculation rate as high as possible without breakage of flocs is called 'tapered flocculation'. In the present work, an attempt has been made to compare the performance of continuous tapered flocculation in conical and cylindrical tanks. The efficiency of conical flocculator was found to be higher than that of cylindrical flocculator, especially at higher flow rates.

The flocculation and coagulation processes play an important role in water treatment systems for public water supply as well as industries. Coagulation and flocculation facilitate the removal of turbidity, colour, odour and taste from water. 'Perikinetic flocculation' is a term reserved for floc formation brought about by Brownian motion whilst 'orthokinetic flocculation' is used to describe flocculation achieved by imparting velocity gradients to the dispersion through stirring. It is commonly observed that gentle stirring promotes flocculation of particles which have been destabilised and which may have commenced to aggregate by Brownian motion. This is due to the velocity gradients which are induced in the liquid causing relative motion and, therefore, collisions between the particles are present. Such flocculation caused by fluid motion is called 'orthokinetic' to differentiate it from that caused by Brownian motion called 'perikinetic'.

The magnitude of the velocity gradient ($G$) is limited by the possibility of large flocs being broken by shear stress. The material constituting the flocs and the conditions under which they are formed both affect their shear strength. Flocs formed rapidly under intense velocity gradients are usually more compact and, therefore, stronger than those formed in lower velocity gradients. As flocs become larger, they tend to become less dense and more susceptible to shear.

To maximise the rate of flocculation without break-up as the flocs grow in size, a flocculation scheme could be followed where a high velocity gradient is applied when the flocs are small in size. As these grow, they approach the break-up zone and $G$ is reduced allowing further growth in the aggregation zone. This progressive reduction of $G$ to keep the flocculation rate as high as possible, but below the break-up zone, is called 'tapered flocculation'.

The earlier works on tapered flocculation concentrated mainly on batch systems. Of late, tapered flocculation in continuous systems has attracted the attention of environmental engineers. In the present work, an attempt has been made to compare the effectiveness of two types of flocculators—conical and cylindrical in tapered flocculation in an effort to suggest an optimum model.

**Experimental Procedure**

Two flocculators of equal volume were fabricated from clear perspex, one of conical shape and the other of cylindrical shape with dimensions as shown in Figs 1 and 2, respectively. The experimental set up for continuous flocculation is illustrated in Fig. 3.
The influent is fed from the bottom of the flocculator which has a shaft mounted at the centre driven by a motor through belt and pulley arrangement. Four paddles of dimensions (P1 to P4) as shown in Fig. 4 are fixed to the central shaft in such a way that the tapering increases from top to bottom. The speed of the motor for driving the shaft can be varied by a rheostat to study the effect of paddle speed on flocculation.

The studies were made using suspension of bentonite clay. Commercial grade alum [Al₂(SO₄)₃·18H₂O] was used to prepare the flocculant suspension. The dosage of the flocculant was determined based on the flow rate of clay suspension and flocculant. The clay suspension and flocculant solution were stored in two separate feed tanks from where they are pumped to a cup arrangement enroute to the flocculator tanks using a peristaltic pump.

The experiments were carried out with three different speeds of rotation of the paddle, i.e., 30, 50 and 60 rpm, and bentonite clay suspensions having four different initial turbidities, i.e., 50, 100, 200 and 400 NTU. The optimum dose of alum for these suspensions were found out by jar test. Four different flow rates of the clay suspension were 332.5, 443.3, 665, and 110 mL/min. The time required to fill the flocculator volume of 6650 litre at these flow rates were approximately 20, 15, 10, and 6 min, respectively. Corresponding to flow rate of the suspension, the flocculant flow rate required also varies. The flocculant flow rates corresponding to the above suspension flow rates were calculated as 66, 46, 24, and 24 mL/min, respectively.

The conical flocculator was studied first. After fixing the paddle to the shaft, the clay suspension and flocculant were pumped at the required flow rate. A time period of 15 min was allowed for the system to achieve steady-state. A sample of the supernatant liquid was withdrawn and allowed to settle for 15 min. The residual turbidity of the sample was measured using standard method. The same procedure was repeated for the cylindrical flocculator.

Results and Discussion

The results of the experiments are shown in Table 1 and Figs 5-8. In each figure, the ratio of residual turbidity (N) to initial turbidity (N₀) is plotted against initial turbidity (N₀) on a log-log scale.

Effect of paddle shape—As evident from Table 1, the effectiveness of the paddles P1 and P2 was found to be almost the same in both cylindrical and conical flocculators for a paddle speed of 50 rpm. So paddles P3 and P4 were used for further studies with 30 rpm and 60 rpm.
Among P3 and P4, better turbidity removal was obtained with paddle P4. This should be due to the fact that for a given flow rate, more volume of the influent is subjected to flocculation with paddle P4 than with paddle P3. Hence, for the same power input, a larger volume of the influent could be treated with paddle P4 than with other paddles.

**Effect of flow rate of suspension**—From the results obtained for 50 rpm, it is found that the turbidity removal becomes more effective as the flow rate decreases. This may be due to the fact that the time duration for which the particles in suspension are subjected to orthokinetic flocculation at higher flow rates is less than that at lower flow rates.

With the two lowest flow rates, those corresponding to 20 and 15 min, the turbidity removal

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**Table 1—Flocculator performance at 50 rpm paddle speed**

<table>
<thead>
<tr>
<th>Flow time, min</th>
<th>Residual turbidity values in NTU</th>
<th>Conical flocculator</th>
<th>Cylindrical flocculator</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>P1</td>
<td>P2</td>
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<tr>
<td>Initial turbidity, 50 NTU</td>
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<td>6</td>
<td>9.0</td>
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<tr>
<td></td>
<td></td>
<td>10</td>
<td>8.5</td>
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<tr>
<td></td>
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<td>15</td>
<td>8.0</td>
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<td></td>
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<td>20</td>
<td>6.5</td>
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<tr>
<td>Initial turbidity, 100 NTU</td>
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<td>6</td>
<td>9.0</td>
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<td>10</td>
<td>7.5</td>
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<td></td>
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<td>15</td>
<td>6.5</td>
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<tr>
<td></td>
<td></td>
<td>20</td>
<td>6.0</td>
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<tr>
<td>Initial turbidity, 200 NTU</td>
<td></td>
<td>6</td>
<td>15.0</td>
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<td></td>
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<td>10</td>
<td>14.5</td>
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<td></td>
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<td>15</td>
<td>13.5</td>
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<td></td>
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<td>20</td>
<td>11.0</td>
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<tr>
<td>Initial turbidity, 400 NTU</td>
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<td>6</td>
<td>15.5</td>
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<td></td>
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<td></td>
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<td>10.0</td>
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</table>
obtained was almost the same. Therefore, flow rates corresponding to flow time 6 and 10 min were chosen for further studies.

Effect of initial turbidity—From the results, it is found that the higher the initial turbidity of the suspension, the better the efficiency of the flocculator for turbidity removal. This may be attributed to the fact that, under identical conditions of flow rate and speed of rotation of the paddle, the turbidity removal obtained for higher turbidity suspensions is high.

Effect of flocculator shape—From the results obtained for bentonite clay-water system, it is observed that the conical flocculator performs better than a cylindrical flocculator in turbidity removal. In both the flocculators, the velocity gradient \( G \) decreases in going up from the bottom (i.e., tapering of \( G \) takes place). In the cylindrical flocculator, the time of flocculation \( t \) is a constant along the length of the vessel and the product \( Gt \) (dimensionless) decreases. In the conical flocculator, the time of flocculation for the particles increases along the length in going from bottom to top, i.e., tapering of time also takes place. The product \( Gt \) will remain a constant along the length of the conical flocculator due to the tapering of both \( G \) and \( t \).

At constant \( Gt \), the particles are subjected to the same shear force throughout the flocculator whereas at varying \( Gt \) values, the particles along the length of the flocculator tank are not subjected to the same shear forces. This explains the reason for the better performance of conical flocculator.

Effect of speed of rotation of the paddle—On examining the results obtained with bentonite clay-water system, it is found that a speed of rotation of 50 rpm resulted in maximum turbidity removal. As the speed of rotation of the paddle increases, the degree of agitation to which the suspension is subjected also increases. This results in more collisions between the particles and formation of larger flocs. But there seems to be a limiting velocity gradient. If the velocity gradient is higher than the limiting value the flocs will tend to break. This explains the reason for the maximum turbidity removal obtained with 50 rpm.

Conclusion

The present study leads to the conclusions that the higher the initial turbidity of the suspension, the better will be the efficiency of the flocculator for turbidity removal and as the flow rate of the influent increases, the turbidity removal achieved decreases. Moreover, the efficiency of conical flocculator is found to be higher than that of cylindrical flocculator. The difference is more predominant at higher flow rates of the suspension. Among the three paddle speeds 30, 50 and 60 rpm, 50 rpm is found to be the most effective in turbidity removal.

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