CHAPTER 5
TAPERED FLOCCULATION IN CONTINUOUS FLOW SYSTEM
5.1 INTRODUCTION:

Coagulation and flocculation processes play an important role in any water treatment plant. Coagulants when added disturb stabilized colloidal system of water. Rapid mixing or flash mixing quickly disperses coagulant in raw water and forms primary flocculation particles after destabilizing double boundary layer. Flocculation induces primary particles to come together to form larger flocs.

Efficiency of settling tank and filters greatly depends upon the performance of flocculator. Extent of mixing and velocity gradients are important parameters affecting the flocculation process. In conventional flocculation, normally velocity gradient is uniform throughout the process. Constant higher velocity gradient throughout the time of flocculation leads to denser flocs which settle quickly. However these flocs do not grow in size. On the contrary, uniform lower velocity gradients during entire period of flocculation increases floc size, but such flocs are lighter and takes considerable time to settle and hence these flocs are likely to breakup and thus reduce efficiency of conventional flocculator. Fair and Geyer (1968) has suggested values of velocity gradients between 10 to 75 sec$^{-1}$ and the values of the dimensionless product of velocity gradients and flocculation time between $10^4$ to $10^5$ for better results in conventional flocculation.
Tapered flocculation has therefore been considered as an alternative to the conventional flocculator. Kawamura (1976) mentioned that tapered flocculation resulted in saving of 30% to 40% quantity of alum. Bhole (1979) prepared mathematical model to compare theoretically the efficiency of tapered flocculation with uniform flocculation and found tapered flocculation as more efficient. Velocity gradient in tapered flocculation is gradually reduced in the direction of flow. High velocity gradient at the inlet increases particle contact frequency resulting in denser flocs. Gradual reduction of velocity gradient avoids breaking of flocs and thus floc size increases. Hence, principal advantage of tapered flocculation is that it forms large and dense flocs which settle quickly and has an ability to remove most of the turbidity.

Several attempts have been made to achieve tapered flocculation in a continuous flow system in non mechanical type flocculators. Schulz et.al. (1984) mentions various methods. In Cochabamba (Bolivia) and Oceanside (in Arcadia, California) plants, tapered flocculation is achieved by changing spacings of the baffles. Close spacing at inlet and wider spacing at outlet produces high and low velocity gradients respectively. In helicoidal flow flocculators tapered velocity gradients are produced by increasing areas of inlet openings for successive chambers. Bhole & Ughade (1981) designed tapered velocity gradient gravel bed flocculator by varying cross sectional area of bed and also by changing the grade of gravels.
Mechanical (paddle) flocculators are generally preferred to nonmechanical flocculators due to their greater versatility. Eventhough there is variation in the flow, temperature or raw water quality, speed of paddles of mechanical flocculators can be adjusted to suit these variations. Another advantage of mechanical flocculator is that it is more efficient than nonmechanical flocculator for large capacity treatment plants. A very little literature is available concerning tapered velocity gradient flocculation particularly in continuous flow mechanical paddle type flocculators. Objective of present work is to intorduce the modified concept of tapered velocity gradient in paddle flocculators for the continuous flow system.

5.2 MECHANICAL FLOCCULATOR (VARIOUS PARAMETERS)

In medium and large capacity water treatment plants, generally, flocculation and sedimentation are combined to shorten the time of transfer of flocculated suspension to a settling tank such treatment unit is thus known as a 'Clariflocculator'. Most common type of paddle flocculators is shown in figure 5.1.

5.2.1 Power consumption:

The expression for power input (P) of an impeller is

\[
P = \frac{1}{2} C_D \theta A v^3
\]

--5.1

\[
v = V - KV
\]

--5.2

\[
V = \frac{2 \pi r N}{60}
\]

--5.3
where:

\[ CD = \text{coefficient of drag}, \]
\[ \gamma = \text{mass density of fluid}, \]
\[ A = \text{area of paddle} \]
\[ V = \text{relative velocity between paddle and fluid} \]
\[ V = \text{actual velocity of paddle} \]
\[ K = \text{ratio of fluid velocity to the velocity of paddle} \]
\[ r = \text{effective paddle radius} \]
\[ N = \text{rotational speed of paddle per minute} \]

Substituting eqn 2 & 3 in eqn 1 we get

\[
P = \frac{1}{2} CD \gamma \left[ \frac{2 (1-K)N}{60} \right]^3 A r^3 \tag{5.4}
\]

or

\[
P = C N^3 A r^3 \tag{5.5}
\]

For series of paddles rotating at constant rpm 'N', in the system, the equation (5) can be written as

\[
P = C N^3 \Sigma A r^3 \tag{5.6}
\]

where:

\[ C = \frac{1}{2} CD \gamma \left[ 2 \frac{\pi}{60} (1-K) \right]^3 \]

5.2.2 Effective Volume And Velocity Distribution

In conventional flocculator the velocity of fluid at any point on paddle linearly increases from minimum at inner edge to maximum at outer edge, as given by eqn (5.3). Thus the fluid particles moved by inner paddle will have minimum velocity, whereas those moved by outer paddle will have maximum velocity. But in the gap between the paddles, drop in velocity is observed depending on its distance from the edges

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of the paddles. These circles of drop in the velocity are assumed to be the traces of hypothetical cylindrical compartment walls, used for calculating the effective volume disturbed by each paddle. Theoretically, it is difficult to find out the exact location of these hypothetical walls; but for simplicity, it can be assumed to be present at the mean of effective radii of two adjacent paddles. The velocity distribution pattern will be as shown in Fig. 5.2.

5.2.3 Velocity Gradient

Camp (1943) has formulated an equation for velocity gradient (G) which is given by:

\[ G = \left( \frac{\text{Power per unit volume}}{\text{Dinematic viscosity}} \right)^{1/2} \]

or

\[ G = \left( \frac{P}{\mu \cdot \text{vol}} \right)^{1/2} \]

where \( \mu \) is the dynamic viscosity of the fluid.

Substituting the value of \( P \) from eqn (5.6) in eqn (5.7)

\[ G = Z \left( \frac{N^3 \cdot A \cdot r^3}{\text{vol}} \right)^{1/2} \]

or

\[ G^2 = Z^2 \left( \frac{N^3 \cdot A \cdot r^3}{\text{vol}} \right) \]

where

\[ Z = \left( \frac{C}{\mu} \right)^{1/2} \]

5.2.4 Pattern Of Velocity Gradient In Conventional Flocculator

In the existing "Door-Oliver" type mechanical flocculator as shown in Fig. (5.1) the paddles are of the same shape and size. Thus the water has two velocity components horizontally from central inlet to periphery of tank and vertically from top to bottom of the tank. The depth of the tank being small compared to radius, the flow of water in large tanks can almost be treated as horizontal. It can be seen from equation (5.6) that the power consumption of paddles
away from centre is more than that near the centre. (i.e. power consumption of paddles increases with its distance from centre) due to increase in effective radius. Similarly, the volume swept by the paddles (Volume of the compartment), also increases from centre to periphery. Here, one may wrongly conclude that this increase in volume in denominator of eqn. (5.7) nullifies effect of paddle radius in the numerator. But the power varies with cube of 'r' whereas volume varies with square of r resulting in net increase in value of G from centre to periphery (i.e. with increase in 'r'). Hence velocity gradient is low near the inlet, and is maximum at periphery. Thus exactly reverse tapered flocculation than contemplated takes place in case of existing mechanical flocculator.

5.3 NEW PROPOSED METHODS FOR TAPERED FLOCCULATION IN CONTINUOUS FLOW MECHANICAL FLOCCULATOR

It is seen that the velocity gradient in the existing flocculators increases in the direction of flow, resulting in reverse tapered flocculation. In the proposed flocculator various methods are described, for achieving the desired tapered flocculation. All these methods are mainly intended to improve the existing reverse tapered flocculation process, resulting in comparatively less increase in 'G' along the direction of flow or decrease in 'G' along the direction of flow (as desired for tapered flocculation). Normally, more than one method are simultaneously applied to achieve the desired results. All these methods are evolved from eqn(8). These methods are 1-
1> Reduction in 'r' along the direction of flow.
2> Reduction in 'N' along the direction of flow.
3> Increase in 'vol' along the direction of flow.
4> Reduction in 'A' along the direction of flow.
5> Reversing the direction of flow.

All these methods are described in the subsections with an illustrative example of a flocculator of dimensions shown in Fig. 5.1. As the paddles are equispaced the volume of the hypothetical vertical compartments increases from centre to periphery. Hence in case II and IV one of the methods combined with volume increases method (case III) is illustrated. In case one the compartments are assumed to be horizontal and direction of flow to be vertically downward. The values of velocity gradient 'G' for all the following four cases have been computed.

Case I>. The value of 'r' is reduced by reducing the height paddles (i.e. A) keeping 'N', and vol as constant.
(N = 1.5 rpm, vol = 242 m³) along the direction of flow. (assumed as vertically downward)

Case II>. The values of 'N' are varied from N = 3 rpm to 0.5 rpm, along with increase in volume (as in case III), along the direction of flow keeping A as constant.
(A = 0.7 x 3.5 m).

Case III>. The values of 'vol' are varied (from 110 m³ to 374 m³) along the direction of flow, keeping 'N' and 'A' as constant. (N = 1.5 rpm, A = (0.7 x 3.5)m)

Case IV>. The values of 'A' are varied from A = 3.5 x 3.5 m
to 0.2 x 3.5 m along with increase in volume (as in case-III), along the direction of flow keeping N as constant. (N = 1.5 rpm).

5.3.1 Reduction In The Paddle Radius ‘r’ Along The Direction Of Flow.

This method is theoretically very effective method, as can be seen from eqn. (4.8), where \( B^2 \) varies with cube of ‘r’. Thus, reducing value of \( r \) along the direction of flow can produce significant drop in value of ‘B’, resulting in tapered flocculation. The impact of ‘r’ on ‘B’ is more compared to impact of ‘A’ or ‘vol’ as seen from eqn. (5.8).

In the existing flocculator, the flow is diagonally downwards which is almost treated horizontal as discussed earlier. This method can not be directly applied in the existing system where flow is almost horizontal and increase in value of ‘r’ along the horizontal direction of flow is unavoidable. But if the flow is assumed as vertically downwards, (where depth of flocculator is more compared to radius), this method can be applied by arranging paddles of varying heights as shown in Fig. 5.3. The volume of each hypothetical horizontal compartment is kept constant, selecting equal spacing between them. In each subsequent downward compartment from top to bottom, the fourth, third and second paddle (area) is missing, consequently resulting in elimination of the terms \((r4)^3\), \((r3)^3\) and \((r2)^3\) in the second, third and fourth compartments while calculating the value of ‘B’. Hence, tapered flocculation results in downward direction and the value of B drops from 60 sec\(^{-1}\) to 8 sec\(^{-1}\).
EFFECTIVE RADIUS REDUCTION

FIG. 53

REDUCTION OF AREA

FIG. 54
from top to bottom as seen in case I. Even when the flow is considered downward, though theoretically there is drop in value of \( G \) in downward direction, this method has a serious technical drawback of producing, an undisturbed lower outer triangular portion, which acts as a sedimentation basin rather than a flocculation basin, resulting in sedimentation of flocs. Hence this method is not feasible.

5.3.2 Reducton In Rotational Speed 'N' Of Paddles Along The Direction Of Flow

It can be seen from eqn. (5.8) that \( G^2 \) varies with the cube of \( N \). Therefore a slight variation in value of \( N \) causes greater variation in value of \( G \). Theoretically this method is very effective and any change in value of \( G \) can be obtained for selected value of \( A, r \) and vol., by correct selection of \( N \). The only restriction in selecting the value of \( N \) for desired value of \( 'G' \) is availability of desired speed in the driving mechanism. The effect of change in value of \( N \) on the value of \( 'G' \) can be seen from case II of the illustrative example given in subsequent section. In the case II four different speeds are selected to achieve the tapered flocculation by this method. The number of speed variations can be reduced to half i.e. paddles in compartment I and II can be rotated at speed of \( N_1 \) rpm, where as paddles in compartment III and IV can be rotated at speed of \( N_2 \) rpm (where \( N_2 < N_1 \)). The reduction in value of \( 'G' \) between the compartments I and II and between the compartments III and IV can be obtained by applying the area reduction method.
\[ N_1 > N_2 > N_3 > N_4 \]

REDUCTION IN R.P.M.

FIG. NO. 54
described in section 5.3.4. Thus, the complications in mechanism can be slightly reduced by reducing the speed changes. This method however involves complicated mechanisms, high capital cost, high maintenance cost etc. Hence this method is normally recommended after carrying out the feasibility study of the setup.

5.3.3 Increase In Volume Swept By The Paddles Along The Direction Of Flow

As seen from eqn. (5.8), one of the method can be to increase the volume swept by the paddles along the direction of flow, to achieve tapered flocculation. But the volume change has little impact on the change in the value of G compared to earlier two methods. Hence individual application of this method is not recommended in the flocculators. The impact of this method is further reduced (to the extent of achieving reverse tapered flocculation) due to unavoidable increase in value of 'r' along the horizontal direction of flow (though it is undesirable). The effect of individual application of this method can be seen from case III of the illustrative example given in the subsequent section. The value of G increases from 21 sec\(^{-1}\) to 73 sec\(^{-1}\), though volume is increased from 110m\(^3\) to 374m\(^3\) resulting in reverse tapered flocculation. This method though individually ineffective can be used to enhance the tapering effect coupled with other methods as seen in case II or case IV.
3.4 REDUCTION IN PADDLE AREAS ALONG THE DIRECTION OF FLOW

This method like last method has also less impact on value of $G$ to achieve desired tapered flocculation. As seen from eqn. (5.8) $G^2$ varies directly with $A$ and hence change in value of $A$ causes very little change in value of $G$. This method is individually less effective in the existing type of flocculator because of unavoidable increase in the value of $r$ along the direction of flow, but it can be conveniently applied in the existing situations coupled with volume increase method. This method is illustrated in case IV of the illustrative example given in the subsequent section. It can be seen that when area is reduced from $(3.5 \times 3.5) \text{m}^2$ to $(0.2 \times 3.5) \text{m}$ along with increase in volume from $110\text{m}^3$ to $374\text{m}^3$ the drop in value of $G$ is very small from $48 \text{Sec}^{-1}$ to $39 \text{Sec}^{-1}$ along the direction of flow. It can be seen that though the drop in value of $G$ is not significant, this method is preferred because i) It is easy to change the paddle areas along the direction of flow in the existing system with little modifications, and ii) The reverse tapering which was present when equal (as in case III) paddle areas were used is atleast avoided.

5.3.5 Reversing The Direction Of Flow

It can be seen that in the existing system the value of $G$ increases from centre to periphery along the direction of flow (i.e. the reverse tapered flocculation than contemplated takes place). This can be seen from case III of the
illustrative example given in the subsequent section. Further this central inlet system has a drawback of decrease in velocity of flow from centre to periphery (i.e. as the floc formation proceeds), resulting in settling of flocs in the flocculation basin, thereby reducing rate of flocculation. If the direction of flow in the existing system is reversed (i.e. instead of central inlet and peripheral outlet if peripheral inlet and central outlet is used), the tapering of the 'G' will take place in the desired direction. Due to flow of fluid from periphery to centre the velocity of flow also increases along the direction of floc formation, avoiding the problem of sedimentation of flocs in the flocculation basin, such radial-peripheral inward flow pattern can achieve the desired tapered flocculation in the existing system. Thus, with this method the velocity gradient will be higher in the earlier compartments, decreasing towards centre.

5.4 ILLUSTRATIVE EXAMPLE

A flocculator of dimensions shown in Fig. (5.1) is considered for illustrative purpose. It is the clariflocculator with eight equispaced paddles mounted on the flocculator arm at various effective radii 2.5m, 4.5m, 6.5m & 8.5m. For calculating the volume swept by each paddle, the method stated in the section 2.2 is used. Thus, the first compartment will have inner radius of 1.5m, considering the central inlet & other mechanism and the outer diameter i.e. the position of hypothetical compartment wall between vertical compartment I and II is at radius of 3.5m, the
successive hypothetical compartment walls are present at 5.5m, 7.5m & 9.5m radii. The following data is assumed for calculation purpose

\[ c_0 = 2.0, \ k = 0.3, \quad = 1000/9.81 \text{ Kg/m}^3 \]
\[ = 1.02 \times 10^{-4} \text{ Kg f sec/m}^2 \]

Substituting these values in eqn. (5.8) value of \( G \) can be calculated by the modified equation

\[ G = \left( \frac{394.126 \times N \times \pi \times r^3}{3 \times \text{vol.}} \right)^{1/2} \]

----5.9

Case - I

The value of \( r \) is reduced in the downward direction (assumed direction of flow) by reducing the height of paddles. Keeping \( N = 1.5 \text{ rpm} \) & \( \text{vol.} = 242 \text{ m}^3 \). The horizontal hypothetical compartments H(I), H(II), H(III), H(IV) have been selected of equal volume by dividing the total paddle height into four equal parts. The calculated values are tabulated in table 5.1.0. Total volume swept by all paddles \[ = \pi \times h \times (9.5^2 - 1.5^2) = 968 \text{ m}^3 \]

Volume of each horizontal compartment = \( 968/4 = 242 \text{ m}^3 \)

Area of each paddle present at different radii in each compartment \[ = (0.7 \times 3.5)/4 = 0.61 \text{ m}^2 \]

Thus, from equation (9)
\[ G = (394.126 \times 1.5^3 \times 0.61 \times r^3/242)^{1/2} \]
\[ = (3.36 \ r^3)^{1/2} \]
<table>
<thead>
<tr>
<th>Horizontal Effective radii</th>
<th>G = [(3.36\times r^3)^{1/2} \text{ s}^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campartmt. r1 r2 r3 r4</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>m m m m</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>HI 2.5 4.5 6.5 8.5</td>
<td>[ (3.36(2.5^3 + 4.5^3 + 6.5^3 + 8.5^3))^{1/2} ]</td>
</tr>
<tr>
<td></td>
<td>= 60.00</td>
</tr>
<tr>
<td>HII 2.5 4.5 6.5 ---</td>
<td>[ (3.36(2.5^3 + 4.5^3 + 6.5^3))^{1/2} ]</td>
</tr>
<tr>
<td></td>
<td>= 36.00</td>
</tr>
<tr>
<td>HIII 2.5 4.5 --- ---</td>
<td>[ (3.36(2.5^3 + 4.5^3))^{1/2} ]</td>
</tr>
<tr>
<td></td>
<td>= 19.00</td>
</tr>
<tr>
<td>HIV 2.5 --- --- ---</td>
<td>[ (3.36(2.5^3))^{1/2} ]</td>
</tr>
<tr>
<td></td>
<td>= 8.00</td>
</tr>
</tbody>
</table>

Case II: The values of N are varied from N = 3.0 rpm to 0.5 rpm, along with increase in volume (as in case III) along the direction of flow keeping A as constant = .7 x 3.5 m. The values of vertical compartments, the effective radii and values of G calculated by eqn. (5.9) are tabulated in Table 5.2.

<table>
<thead>
<tr>
<th>Vertical Compartment</th>
<th>Vol. ( ^3 )</th>
<th>A ( ^2 )</th>
<th>N rpm</th>
<th>G \text{ s}^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>110</td>
<td>0.7 x 3.5</td>
<td>3.0</td>
<td>60</td>
</tr>
<tr>
<td>II</td>
<td>198</td>
<td>--&quot;--</td>
<td>1.5</td>
<td>38</td>
</tr>
<tr>
<td>III</td>
<td>286</td>
<td>--&quot;--</td>
<td>1.0</td>
<td>30</td>
</tr>
<tr>
<td>IV</td>
<td>374</td>
<td>--&quot;--</td>
<td>0.5</td>
<td>14</td>
</tr>
</tbody>
</table>

Case III: The values of 'vol.' are increased from 110 m\(^3\) to 374 m\(^3\) along the direction of flow keeping A & N constant. The values calculated by eqn. (5.9) are tabulated in Table 5.3.
Table 5.3

<table>
<thead>
<tr>
<th>Vertical Compartments</th>
<th>Vol. m³</th>
<th>A m²</th>
<th>N rpm</th>
<th>B s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>110</td>
<td>0.7x3.5</td>
<td>1.5</td>
<td>21</td>
</tr>
<tr>
<td>II</td>
<td>198</td>
<td>--&quot;--</td>
<td>1.5</td>
<td>38</td>
</tr>
<tr>
<td>III</td>
<td>286</td>
<td>--&quot;--</td>
<td>1.5</td>
<td>56</td>
</tr>
<tr>
<td>IV</td>
<td>374</td>
<td>--&quot;--</td>
<td>1.5</td>
<td>73</td>
</tr>
</tbody>
</table>

Case IV: The values of paddle areas are reduced from 3.5x3.5 m to 0.2x3.5 m along with increase in volume, keeping N = 1.5 rpm, as constant. The value of B calculated from eqn. (5.9) are tabulated in Table 5.4.

Table 5.4

<table>
<thead>
<tr>
<th>Vertical Compartments</th>
<th>Vol. m³</th>
<th>A m²</th>
<th>N rpm</th>
<th>B s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>110</td>
<td>3.5x3.5</td>
<td>1.5</td>
<td>48</td>
</tr>
<tr>
<td>II</td>
<td>198</td>
<td>1.0x3.5</td>
<td>1.5</td>
<td>46</td>
</tr>
<tr>
<td>III</td>
<td>286</td>
<td>0.4x3.5</td>
<td>1.5</td>
<td>42</td>
</tr>
<tr>
<td>IV</td>
<td>374</td>
<td>0.2x3.5</td>
<td>1.5</td>
<td>39</td>
</tr>
</tbody>
</table>

5.5 COMPUTER AIDED DESIGN

The computer programme for designing a tapered clarifier is prepared for speed variation method. Using this programme the calculation involved in the process of design are reduced to a great extent. This leads to saving of design time. The complete computer programme is given in the ANNEXTURE-I.
5.6 CONCLUSION

The advantages of tapered flocculation are explained and proved by many research workers. It is evident that in the existing design of clariflocculator tapering of flocculation takes place in reverse way than contemplated. No attempts are made to achieve the concept of tapered flocculation in continuous flow mechanical flocculators. This chapter explains the various methods for achieving desired tapered flocculation in continuous flow paddle flocculator.