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Design of around-the-end hydraulic flocculators

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ABSTRACT: Hydraulic flocculators, despite their superior plug-flow properties, negligible energy requirements and robust simplicity, are commonly perceived as being inflexible. Once built, it is argued, they do not provide the operational flexibility to compensate for flow fluctuations or changing raw water characteristics. The design procedure developed in this paper demonstrates the contrary, namely that hydraulic flocculators can be designed to satisfactorily cope with tapered velocity gradients, flow variations and water quality variations. The procedure is based on a two-step approach; the horizontal layout is first determined with average values for velocity gradient and water depth; then only the floor slope and exact water depths are determined to enable satisfactory flocculation for all design scenarios.

NOMENCLATURE

B	Channel width (m)
D	Water depth (m)
G	Velocity gradient (s^{-1})
N	Number of channels (–)
p	Slot width ratio, with respect to B (–)
q	Overlap ratio, with respect to B (–)
Q	Flow rate ($m^3 s^{-1}$)
r	Average water depth ratio, with respect to B (–)
t	Flocculation time (s)
v	Channel velocity (m/s)
V	Water volume (m^3)
w	Baffle thickness (m)
Δh	Head loss across one turn (m)
ΔH	Head loss across the flocculator (m)
ΔS	Difference in floor level across the flocculator (m)
ρ	Density of water (kg/m^3)
ν	Kinematic viscosity of water (m^2/s)
μ	Dynamic viscosity of water (kg.m/s)

INTRODUCTION

Hydraulic flocculators, in the form of around-the-end-baffled channels, offer the significant benefits of plug flow, and do not require electromechanical equipment and maintenance. They are not, however, universally adopted for two main reasons:

- Hydraulic flocculators are, along with other static mixing devices, inflexible once they are built. The consequent perception is that they neither provide optimal flocculation at flow rates other than design flow, nor are able to provide different levels of energy input if conditions so require.
- Despite their apparent simplicity, their design requires practical guidelines which are not readily available.

This paper demonstrates that around-the-end hydraulic flocculators are inherently much more flexible and versatile than generally perceived, provided that they are thoroughly analysed and designed. In order to provide the engineer with some tangible tools for analysis and design, the paper covers the following main points:

- The identification of the primary design variables for hydraulic flocculators,
- A review of the practical ranges for each variable, based on the published literature and a South African treatment plant survey,
- A design procedure for the horizontal flocculator layout, based on the average velocity gradient and average water depth,
- A design procedure for the exact determination of the required flocculator floor slope and water depths for any given flocculation requirement, and
- Five worked examples to demonstrate how the same horizontal flocculator layout can be adapted to meet widely varying flocculation requirements.

METHODS AND MATERIALS

Hydraulic flocculator geometry: definition of geometrical variables

A schematic plan of a hydraulic flocculator is shown in Fig. 1, using identical baffles and constant baffle spacing throughout. In this paper the term 'flocculator' will be used for the entire reactor, and the term 'channel' for the sections between baffles. Five geometrical variables are required to define the plan layout of the flocculator (Fig. 1):

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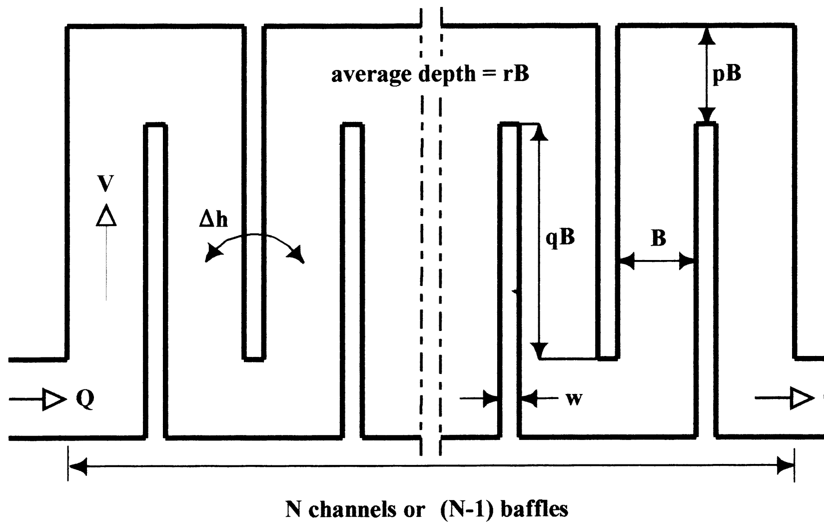

Fig. 1 Schematic layout of an around-the-end hydraulic flocculator, showing the notation used in this paper.

N = number of channels, thereby fixing the number of baffles at $(N-1)$
B = the channel width between baffles
p = the slot width ratio (with respect to B)
q = the overlap ratio (with respect to B)
w = the baffle thickness

Two additional variables are needed for a complete description of the flocculator, namely the flow depth at different points in the flocculator, and the slope of the flocculator floor. These two additional variables, as will be shown shortly, require special analysis. For the purposes of sizing and spacing the baffles within the hydraulic flocculator, however, the following (temporary) simplifying assumptions are made:

- The flow depth, and thus flow velocity, is assumed to be constant at all points in the flocculator. This flow depth is defined as a fraction r of the channel width B.
- The bottom slope, is assumed to be zero, i.e. a perfectly horizontal floor. The floor level difference (ΔS) between the inlet and the outlet of the flocculator is therefore zero.

These assumptions are only necessary to obtain the dimensions of the baffles in plan. For the detailed analysis of the flocculator, which is required after the horizontal layout has been designed, these assumptions will be negated.

Survey of published design examples

To get a perspective on the typical ranges of the different design variables, ten published design examples from four sources will be used for illustration in Table 1. Example D1 is taken from an older text [1]. Examples D2 to D4 [2] and examples D5 to D7 [3] are, in both cases, three consecutive stages of a single facility designed for tapered flocculation. Examples D8 to D10 have been recently published [4] to illustrate the use of design nomograms over a wide range of flow rates.

Survey of full-scale South African water treatment plants

To supplement the literature examples in Table 1, a number of

Table 1 Published design examples for hydraulic flocculators

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Flow rate Q (m^3/s)	0.283	0.500	0.500	0.500	0.116	0.116	0.016	0.010	0.100	1.00
Velocity gradient G (s)	40	70	35	20	50	35	25	50	50	50
Flocculation time t (s)	1800	500	500	500	420	420	420	1000	1000	1000
Number of channels N (–)	20	22	18	14	23	17	14	18	18	18
Channel width B (m)	0.763	2.590	3.170	4.070	0.450	0.62	0.770	0.288	0.944	2.86
Slot width ratio p (–)	0.33	0.21	0.31	0.36	1.51	1.50	1.56	0.52	0.50	0.52
Baffle overlap ratio q (–)	26.3	0.82	0.09	−0.18	9.11	6.06	4.49	44.1	12.8	3.50
Water depth ratio r (–)	3.20	0.77	0.63	0.49	2.22	1.61	1.30	0.52	0.50	0.52
Channel velocity v (m/s)	0.152	0.097	0.079	0.061	2.257	0.187	0.150	0.233	0.225	0.23
Time per turn (s)	95	24	29	38	19	26	32	59	59	59

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Table 2 Design parameters for South African full-scale hydraulic flocculators

	P1	P2	P3	P4	P5	P6	P7	P8
Flow rate Q (m^3/s)	1.389	0.058	0.231	0.174	0.695	0.174	0.174	0.174
Flocculation time t (s)	630	279	576	619	331	76	244	115
Number of channels N (–)	19	29	43	26	17	6	17	7
Channel width B (m)	2.000	0.370	0.900	1.175	1.400	0.680	0.870	1.174
Slot width ratio p (–)	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00
Baffle overlap ratio q (–)	2.70	1.51	0.89	1.33	1.88	3.74	2.48	1.32
Water depth ratio r (–)	1.20	2.82	1.39	0.74	1.24	1.18	0.82	0.56
Channel velocity v (m/s)	0.289	0.150	0.205	0.169	0.287	0.318	0.278	0.227
Time per turn (s)	33	10	13	24	19	13	14	18

full-scale South African water treatment plants were surveyed during 1993 and 1994. The results of this survey are summarised in Table 2. Examples P1 to P5 are flocculators at five different plants, while examples P6 to P8 form three stages of a system designed for tapered flocculation. These plants were designed over a period of 15 years (GFJ Consulting Engineers, 1997).

Practical values for the number of channels (N)

The head loss across a flocculator is directly proportional to the number of turns. The number of channels is therefore the single most important variable to be calculated. The usual method of calculation is to guess a number of channels, and then check the flocculation time and head loss against what is required. This is carried out iteratively until a satisfactory solution is obtained. In order to eliminate these tedious calculations, a series of nomographs was developed from which solutions can be directly obtained [4], but these graphs are limited to only a few specific cases.

A rational approach for a preliminary estimate of the number of channels would be to consider the mean hydraulic retention time per channel. If too few channels are used, each separated by a high energy input, one would move towards the undesirable condition where flocculation is not a relatively even, continuous process, but a process of relative quiescence punctuated with severe energy pulses.

The median value for the published examples is 35 s/channel (range 19–95 s), as opposed to 16 s/channels (range 10–35 s) for the surveyed South African plants. Translated into process considerations, this means that the South African plants, with more frequent, and consequently smaller energy inputs, come closer to the ideal case where mixing energy is evenly and continuously applied.

Practical values for the channel width (B)

The channel width, as the problem is formulated here, is the master variable which also determines the slot width (ratio p), the baffle overlap length (ratio q) and the average flow depth (ratio r). The only limitation to the channel width is a practical one; if too narrow, it may become difficult to construct or clean the channel. For this reason, minimum values of 750 mm [2] and 450 mm [3] had been proposed. The latter values is perhaps more realistic as Table 2 indicates that channel widths as low as 370 mm are used, apparently without creating an operational problem.

Practical values for the average water depth ratio (r)

The average water depth, as stated before, is merely an average value based on the assumption that the water depth is constant everywhere. In reality, the water depth will be different at different points in the flocculator. It is, however, instructive to consider the approximate range of the average water depth ratio. The median value for the published examples is $r = 0.70$, as opposed to $r = 1.19$ for the surveyed South African plants.

Because manipulation of the water depth offers a practical means of attaining some flexibility with hydraulic flocculators, it is advisable to provide enough depth for a reasonable depth range, say of $r = 1.0$–2.0. Other sources suggest, for the same reason, that the absolute depth should be no less than 1.0 m [3] or 0.9 m [5]. Another more theoretical approach would be to consider the most efficient channel section (defined as offering the maximum discharge per unit area), which would be obtained when the channel width is twice the water depth i.e. $r = 0.50$). This approach was used [4] to design channels with a fixed $r = 0.50$ which are shown as examples D8 to D10 in Table 1. This value, however, is considered to be too low to allow meaningful water depth manipulation.

Practical values for the average channel velocity (v)

Although no firm guidelines for the baffle width B and flow depth $r.B$ respectively have been published, there are specific guidelines for the average channel velocity v which is a function of both B and r. Three ranges have been suggested; 0.15–0.45 m/s [1,2], 0.10–0.30 m/s [3], and 0.10–0.40 m/s [5]. Another suggestion is that the channel velocity should be high enough to prevent floc settling; which is estimated to be the case at a velocity between 0.15 and 0.30 m/s [4]. The median values in Tables 1 and 2 are 0.17 and 0.25 m/s respectively, within all the suggested ranges.

Practical values for the slot width ratio (p)

There is wide divergence in opinion on what the slot width ratio should be. In one reference [2] it is treated as a variable which is calculated for each case, independent of the other channel dimensions. More commonly, however, it is considered to be a constant fraction of the channel width. Table 2 indicates that, for the surveyed South African plants, the slot width is commonly fixed at the baffle width, i.e. $p = 1.00$. All South African plants surveyed, however, were designed by the same consultancy, although the author is aware of several other South African consultants who also consistently use $p = 1.00$. In what appears to be the common design practice in South America [3], the slot width is taken as 150% of the baffle width, i.e. $p = 1.50$. In what appears to be Indian design practice [4], the slot width is taken as one-half the baffle width, i.e. $p = 0.50$. The design examples in Table 1 show four cases where the slot width ratios are even lower than $p = 0.50$.

If the design objective is that energy dissipation around the baffle end should be even and not sharply punctuated, then a case could be made for keeping the channel velocity and the average velocity through the slot fairly similar to keep the water in continuously swirling motion from the moment it enters the turn until well after the turn. Excessively small values for p would turn the hydraulic flocculator into a series of small quiescent channels, with water cascading in discrete steps from the one channel to the next. Excessively large values for p, on the other hand, would invite even larger areas of swirling and dead space in the corners, which is readily observed in any hydraulic flocculator, regardless of the slot width ratio.

Practical values for the overlap ratio (q)

Intuitively, the overlap ratios should have both an upper and a lower limit. If this distance becomes too long, the time between successive turns will become excessively long, leading to discrete energy inputs with long periods in between; an undesirable situation discussed earlier. On the other hand, if this distance becomes excessively short or negative, the water will not be forced through a full 180° turn and will tend to meander in a length-wise direction through the flocculator, perpendicular to the channels.

South African design practice indicates values with relatively little scatter, from $q = 0.9$ to $q = 3.7$, with median $q = 1.7$. The published examples in Table 1, however, show values with extreme scatter, from $q < 0$ (indicating that the baffles do not overlap at all) to as high as $q = 44$ (with the water taking a full minute to travel from one turn to the other), with median $q = 5.3$.

Practical values for the baffle thickness (w)

The baffle thickness has, except for very small channels, a negligible effect on the design equations and is usually ignored during the design process, although it is easy to incorporate as will be done in this paper. It is dictated by the structural design and material of the baffles, and is fixed beforehand by the designer. For normal reinforced concrete, $w = 250$ mm (large flocculators) to $w = 100$ mm (small flocculators). For masonry baffles, values vary between $w = 115$ mm (single course) to $w = 230$ mm (double course). It had been suggested that the baffles should be lightweight and adjustable to enable operational adjustment if needed; in this case decay-resistant timber is preferred over metal parts [3], for which the baffle thickness would only be between 20 and 40 mm.

HEAD LOSS FACTORS FOR 180° TURNS

The head loss, or water level drop, across a turn is generally expressed as a fraction of the velocity head:

$$\Delta h = K \frac{v^2}{2g}, \tag{1}$$

with Δh = head loss across a single baffle (m), K = head loss factor (–), v = average channel velocity (m/s), g = gravitational acceleration (m/s).

From a theoretical view, the flow around a 180° turn could be interpreted as two 90° turns. At each turn, the existing velocity head is completely dissipated, and has to be redeveloped in the new direction. While such an approach may be useful for making first-order estimates of the head loss, the values measured in practice are higher and some empirical guidance is necessary:

- If the slot and channel widths are the same ($p = 1.0$), the theoretical value of K should be exactly 2.0. For design, Kawamura [2] suggests $K = 3.2$–3.5, while Montgomery [6] suggests $K = 3.2$.
- For the case where $p = 1.5$, a range of $K = 2.5$ to 4.0 is suggested [3].
- If the slot is significantly narrower than the baffle width ($p < 1$), the flow will be helicoidal or tangential because the stream of water enters tangentially into each chamber, producing a helicoidal flow pattern toward the outlet downstream of each turn. In this case, K will be 1.5 of the velocity head through the slot [2]. It is not stated at which value of p helicoidal flow can be assumed, and there is probably a gradual shift in the flow regime as p decreases below 1.0.

It stands to reason that the K-value will be affected by the slot width ratio, the average water depth ratio, the temperature (never mentioned in the literature) and to a small extent by the overlap ratio. It has also been found that the baffle thickness has an effect on small channel systems [7]. It is clear that a systematic study will be required before firm guideline values for K can be proposed. In this paper, design equations will be developed for a general value K. Where numerical examples are given, a value of $K = 3.2$ will be used throughout.

DETERMINATION OF THE HORIZONTAL FLOCCULATOR LAYOUT

Derivation of the design equations

Flocculation requirements are specified by the velocity gradient G and the flocculation time t. The general formulation for G is:

$$G = \sqrt{\frac{P}{\mu \Delta V}}, \tag{2}$$

with G = velocity gradient (S^{-}), P = power input (W), μ = dynamic viscosity of water (kg.m/s), V = volume into which power is dissipated (m^3). For work done by water flowing from the upstream to the downstream end of a flocculator, the power term can be replaced by:

$$P = \rho \Delta g \Delta Q \Delta\Delta H, \tag{3}$$

with ρ = density of water (kg/m^3), Q = flow rate (m^3/s), ΔH = water level difference, or head loss across the flocculator (m). Equations 2 and 3 lead to an expression for the head loss in terms of the velocity gradient G and flocculation time t:

$$\Delta H = \frac{\nu}{g} \Delta G^2 \Delta t, \tag{4}$$

with ν = kinematic viscosity of water (m^2/s), t = mean hydraulic retention time, or flocculation time (s). A second expression for the head loss across the flocculator can be obtained from Eqn 1 by formulating the mean channel velocity in terms of the flow rate Q and the average cross-sectional area $r.B^2$:

$$\Delta H = (N-1) \Delta\Delta h = (N-1) \Delta \frac{K}{2g} \Delta \left(\frac{Q}{r \Delta B^2} \right)^2 \tag{5}$$

Note that the head loss due to wall friction is ignored. It can be shown that the wall friction is less than 1% of the head loss due to the 180° turns for typical flow conditions in hydraulic flocculators. Elimination of the head loss from Eqns 4 and 5 yield:

$$\frac{(N-1)}{(r \Delta B^2)^2} = \frac{2 \Delta\nu \Delta G^2 \Delta t}{K \Delta Q^2}. \tag{6}$$

The total volume of the flocculator is additionally constrained by the specified retention time t. The retention time t, in terms of previously defined variables, is given by:

$$t = \frac{\text{volume}}{\text{flow rate}} = \frac{N \Delta r \Delta B^3 (q + 2p) + (N-1) \Delta r \Delta B^2 \Delta p \Delta w}{Q}. \tag{7}$$

Equations 6 and 7 are the two primary equations for fixing the horizontal flocculator layout.

Application of the design equations

A hydraulic flocculator needs the five geometrical variables indicated in Fig. 1 as well as a mean flow depth for a complete definition. Of these six inputs, the baffle thickness and slot width ratio are usually fixed beforehand, and another two inputs are provided by Eqns 6 and 7. This leaves two degrees of freedom which require arbitrary decisions by the designer. A convenient procedure will be demonstrated with an example defined in the first part of Table 3.

The time/channel is deemed to be an important process parameter, as motivated earlier. Assuming an acceptable range of 20–40 s, the overlap ratio and channel width are solved with Eqns 6 and 7 for three flow depth ratios, namely r = 1.0, 1.5 and 2.0 (which covers the range that would be practically acceptable). The resulting matrix of values are shown in Table 4. Using Table 4 and the arguments advanced earlier, an arbitrary solution is chosen, indicated by shaded cells. This choice, after rounding for practical reasons, is shown in the second part of Table 3. The third part of Table 3 summarises the final dimensions for the horizontal flocculator layout. This completes the first part of the design. The next step will be to determine the required floor slopes and exact water depths, for which additional design equations have to be developed.

Table 3 Example for determining the horizontal layout of a hydraulic flocculator. The final dimensions are used for Cases A to E following in this paper

Fixed input parameters	
Flow rate Q (m^3/s)	0.300
Velocity gradient G (s)	40
Flocculation time t (s)	600
Temperature T (°C)	20
Head loss factor K (–)	3.2
Slot width ratio p (–)	1.0
Baffle thickness w (m)	0.100
Rounded choice based on exact values in Table 4	
Number of channels N (–)	20
Channel width B (m)	0.900
Overlap ratio q (–)	4.0
Final dimensions for horizontal layout	
Number of channels (–)	20
Number of baffles (–)	19
Channel width B (m)	0.900
Slot width (m)	0.900
Overlap length (m)	3.600
Baffle width (m)	0.100

Table 4 Design options for the fixed input parameters shown in the first part of Table 3. The preferred ranges are highlighted, and the resulting values for q and B are boxed. These values are rounded to the final values shown in the centre part of Table 3

		Overlap ratio q			Channel width B		
Time/turn (s)	Channels N	$r = 1.0$	$r = 1.5$	$r = 2.0$	$r = 1.0$	$r = 1.5$	$r = 2.0$
20	30.0	−0.07	0.36	0.72	1.444	1.179	1.021
22	27.3	0.29	0.81	1.24	1.409	1.150	0.996
24	25.0	0.69	1.29	1.80	1.377	1.125	0.974
26	23.1	1.11	1.80	2.39	1.349	1.101	0.954
28	21.4	1.55	2.35	3.0-3	1.323	1.080	0.936
30	20.0	2.03	2.04	$\boxed{3.70}$	1.299	1.061	$\boxed{0.919}$
32	18.8	2.53	3.55	4.41	1.277	1.043	0.903
34	17.6	3.06	4.20	5.16	1.257	1.026	0.889
36	16.7	3.61	4.88	5.94	1.238	1.011	0.875
38	15.8	4.19	5.59	6.76	1.220	0.996	0.863
40	15.0	4.80	6.33	7.62	1.204	0.983	0.851

DETERMINATION OF WATER LEVELS AND FLOOR SLOPES

Derivation of the design equations

For the design equations used up to now, two simplifying assumptions were made. Firstly, the difference in water level drop in the flocculator was assumed to be linear with the number of turns. This allowed us to work with the average water depth, and regarding the velocity head between turns (and the head loss across each turn) as constant throughout. Secondly, the floor of the flocculator was assumed to be perfectly horizontal. This will very probably not be the case, as floors are usually constructed with some slope to allow for rapid and complete drainage during cleaning. The next section will derive a number of expressions for the water level, velocity gradient and floor slope at different points in the flocculator.

Water level profile through the flocculator

If the velocity head is not constant throughout the flocculator, the water level will not decrease linearly, but will follow a parabolic profile:

$$Y_n = a\,\Delta n^2 + b\,\Delta n + c, \tag{8}$$

with Y_n = water level in the nth channel, a, b, c = constants. The water level is expressed as only a function of the number of channels, as the actual flow length has very little effect on the head loss. (The assumption is therefore made that wall friction contributes nothing to the head loss, an assumption motivated earlier.) To determine constants a, b and c in Eqn 8, three relationships are required. The first comes from fixing an arbitrary datum line on the water surface ($Y = 0$) at the downstream end of the flocculator ($n = N$), from which follows:

$$c = -a\,\Delta N^2 - b\,\Delta N. \tag{9}$$

The remaining two relationships are obtained from the derivative of the water level at any point on the surface:

$$\frac{\mathrm{d}Y}{\mathrm{d}n} = 2\,\Delta a\,\Delta n + b. \tag{10}$$

This derivative is the head loss per turn. Assuming that water level is positive upwards, but head loss is positive downwards, application of this formula at the first channel yields:

$$\left(\frac{\mathrm{d}Y}{\mathrm{d}n}\right)_1 = \Delta h_1 = -K\,\Delta\frac{v_1^2}{2g} = 2\,\Delta a + b, \tag{11}$$

with subscript 1 depicting conditions at the first channel. The derivative at the Nth channel is likewise taken:

$$\left(\frac{\mathrm{d}Y}{\mathrm{d}n}\right)_N = \Delta h_N = -K\,\Delta\frac{v_N^2}{2g} = 2\,\Delta a\,\Delta N + b. \tag{12}$$

Upon substitution of Eqns 9, 11 and 12 into Eqn 8 and simplification, an expression for Y is obtained:

$$Y_n = \frac{KQ^2(N-n)}{4gB^2(N-1)}\,\Delta\overset{\kappa}{}\,\frac{N+n-2}{D_N^2} + \frac{N-n}{D_1^2}\overset{\lambda}{}, \tag{13}$$

with D_N = downstream water depth, D_1 = upstream water depth. The upstream depth D_1 can also be expressed in terms of the downstream depth:

$$D_1 = D_N + \Delta H - \Delta S, \tag{14}$$

with ΔS = floor level difference between upstream and downstream ends. Equation 14 turns Eqn 13 into:

$$Y_n = \frac{KQ^2(N-n)}{4gB^2(N-1)}\,\Delta\overset{\kappa}{}\,\frac{N+n-2}{D_N^2} + \frac{N-n}{(D_N + \Delta H - \Delta S)^2}\overset{\lambda}{}. \tag{15}$$

Equation 15 can be used to calculate the water level profile throughout the flocculator. The following sections will be devoted to finding expressions for D_N, ΔH and ΔS.

Proportionality amongst the flow depth, velocity gradient and flow rate
A general expression for the velocity gradient G follows from Eqns 2 and 3:

$$G = \sqrt{\frac{g \cdot Q \cdot \Delta H}{\nu \cdot V}} \tag{16}$$

The head loss induced by each turn is dissipated in the water volume V contained within one complete channel:

$$V = B \cdot D \cdot (B \cdot q + 2 \cdot B \cdot p + p \cdot w). \tag{17}$$

Substitute Eqns 1 and 17 into Eqn 16 to get the velocity gradient at any point:

$$G = \sqrt{\frac{K \cdot Q^3}{2 \cdot \nu \cdot B^3 \cdot D^3 \cdot (B \cdot q + 2 \cdot B \cdot p + p \cdot w)}}. \tag{18}$$

From Eqn 18, a useful proportionality is evident:

$$G \propto \sqrt{\frac{Q^3}{D^3}}. \tag{19}$$

When applied between points 1 and 2, Eqn 19 is more explicit:

$$D_1 = D_2 \cdot \left(\frac{Q_1}{Q_2}\right) \cdot \left(\frac{G_1}{G_2}\right)^{2/3}. \tag{20}$$

Conditions at the downstream end
At the downstream end, Eqn 18 leads to an expression for the downstream water depth:

$$D_N = \sqrt[3]{\frac{K \cdot Q^3}{2 \cdot \nu \cdot G_N^2 \cdot B^3 \cdot (B \cdot q + 2 \cdot B \cdot p + p \cdot w)}}. \tag{21}$$

Conditions at the upstream end
At the first channel, where $n = 1$, Eqn 15 gives an implicit expression for the total head loss ΔH:

$$Y_1 = \Delta H = \frac{KQ^2(N-1)}{4gB^2} \cdot \left[\frac{1}{D_N^2} + \frac{1}{(D_N + \Delta H - \Delta S)^2}\right]. \tag{22}$$

With these equations developed, the effect of water depth and bottom slope can be systematically investigated.

Application of the design equations

Five examples will be used to demonstrate the use of the design equations developed above. In all five cases, the same horizontal layout from Table 3 will be used

Case A—constant velocity gradient
If the floor of a hydraulic flocculator were perfectly level, the water depth upstream would be greater than downstream. The channel velocity (and consequently velocity gradient) would then be higher downstream than upstream. To eliminate this effect, the floor slope should be parallel to the water level to ensure an even water depth.

The downstream water depth is calculated first from Eqn 21, knowing what the required downstream velocity gradient must be. In this case, where the floor slope must be parallel to the water level, $\Delta H = \Delta S$. The total head loss is then explicitly solved from Eqn 22 after simplification of the second denominator in brackets. The floor level difference is then rounded to a practical value close to the total head loss. (In this case the flow level difference is rounded to 100 mm, close to the calculated head loss difference of 97 mm.) The upstream velocity gradient is checked by applying Eqn 20 at the upstream and downstream ends respectively, knowing that the flow rates are the same. The total flocculation time is calculated from the flocculator area and the average of the upstream and downstream water depths. The results are summarised in Table 5 and the floor and water profiles shown in Fig. 2.

Case B—tapered flocculation
It follows that floor slope manipulation can be used for more than only attaining a constant velocity gradient. It can also be used to attain a velocity gradient which gradually tapers from high to low. Such a case was published as far back as 20 years ago [8]. For Case B, assume that the upstream velocity gradient of 50/s is required to taper to 30/s at the downstream end. (Note that an average velocity gradient of 40/s is maintained to allow the use of the horizontal flocculator layout in Table 1.)

The downstream water depth is calculated first with Eqn 21. The upstream flow depth is then calculated with Eqn 20 between upstream and downstream ends, knowing that the flow rates are the same. Equation 22 is then used to obtain the total head loss through the flocculator. This requires an iterative procedure available on any modern spreadsheet program. Finally, Eqn 14 is used to calculate the required floor level difference. If a rounded floor level difference is used which is substantially different from the theoretical, it may be necessary to recalculate, in correct sequence, the total head loss with Eqn 22, the upstream flow depth with Eqn 14, and the upstream velocity gradient with Eqn 20. The average flocculation conditions are calculated as before. The results are summarised in Table 5 and the floor and water profiles shown in Fig. 3.

Case C—dealing with reduced flow rates
If the plant runs at a flow rate which is less than the design flow rate, the water will flow slower (longer flocculation time) but with a smaller head loss (lower velocity gradient), assuming that the downstream water depth remains constant. This argument is the one most often used against hydraulic flocculators. This problem, however, can be easily overcome if the plant hydraulics are designed to allow operator or automatic control over the downstream flow depth. Figure 7 shows a partial gradient through a treatment plant. In this case, the water level at the downstream end of the settling tank can be

Table 5 Summary of results for Cases A–E. All calculations based on the horizontal flocculator layout shown in Table 3

	Case A	Case B	Case C	Case D	Case E
Flow rate (m^3/s)	1.0 Q	1.0 Q	0.6 Q	0.6 Q	1.0 Q
Total head loss (m)	0.097	0.097	0.097	0.140	0.159
Floor level difference (m)	0.100	0.750	0.100	0.075	0.100
Downstream flow depth (m)	1.888	2.288	1.133	1.558	1.411
Upstream flow depth (m)	1.885	1.627	1.130	0.909	1.500
Downstream velocity gradient (s^{-1})	40	30	40	25	60
Upstream velocity gradient (s^{-1})	40	50	40	56	56
Average velocity gradient (s^{-1})	40	40	40	40	58
Average flow depth (m)	1.887	1.961	1.131	1.234	1.471
Flocculation time (s)	622	647	622	678	485
Gt product (–)	2.5×10^4	2.6×10^4	2.5×10^4	2.7×10^4	2.8×10^4
Floor and water profile shown in . . .	Fig. 2	Fig. 3	Fig. 4	Fig. 5	Fig. 6

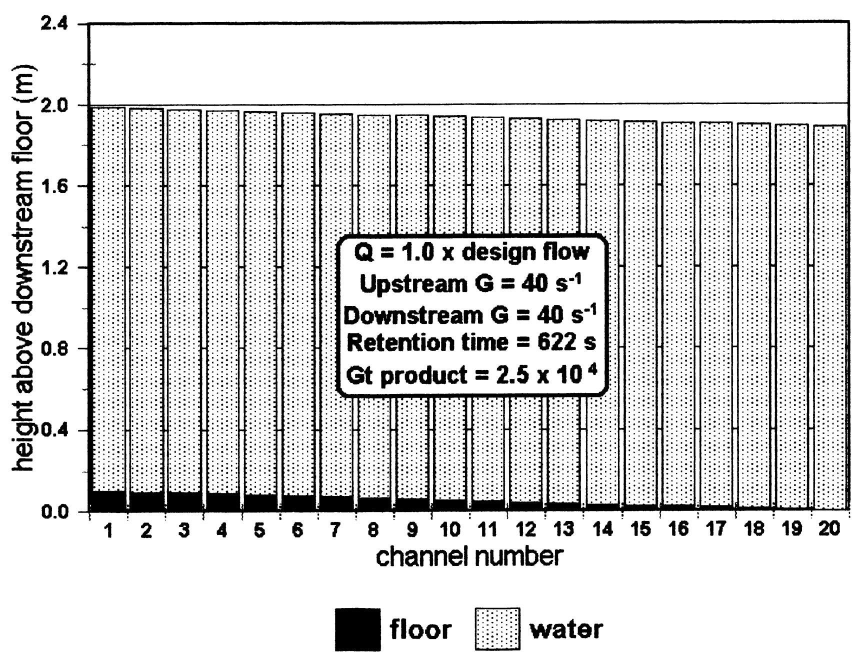

Fig. 2 Floor level and water level profile for Case A.

controlled with an adjustable overflow weir plate. This water level adjustment will be carried through the settling tank to the downstream end of the flocculator. For Case C, the required downstream water depth adjustment will be calculated to maintain approximately equal flocculation conditions when the flow rate drops to 60% of the design flow rate. Assume a constant velocity gradient of 40/s is required with a floor level difference of 100 mm (as determined for Case A).

The downstream water depth at full flow was calculated for Case A. The downstream water depth at reduced flow rate is calculated with Eqn 21. It turns out that water depth is linearly proportional with flow rate if a constant velocity gradient is to be maintained; an observation also evident from Eqn 20. This means that the channel velocity will be same for both cases A and C. The total head loss and upstream flow depth will therefore also be identical to Case A. The flocculation time and *Gt* product are calculated as before. The results are summarised in Table 5 and the floor and water profiles shown in Fig. 4.

Case D—tapered flocculation at reduced flow rate

Case D shows the effect when the flow rate is reduced to 60% of the design flow rate for the Case B flocculator, which was designed for velocity gradients varying from 50/s to 30/s. The floor level difference is therefore also 750 mm for Case D.

A starting value for the downstream water depth is obtained from Eqn 21 by assuming the downstream velocity gradient to be 30/s. The upstream conditions and average velocity gradient

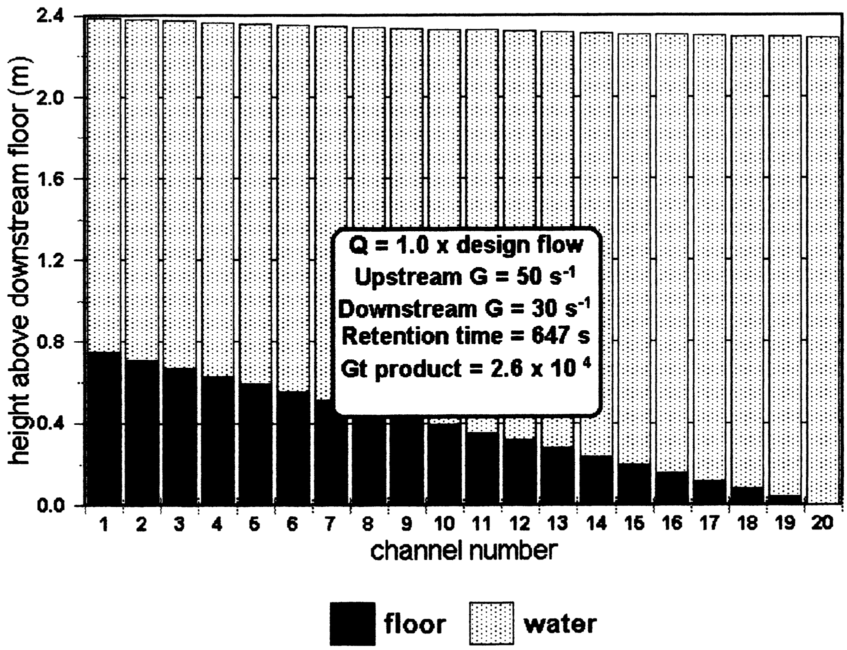

Fig. 3 Floor level and water level profile for Case B.

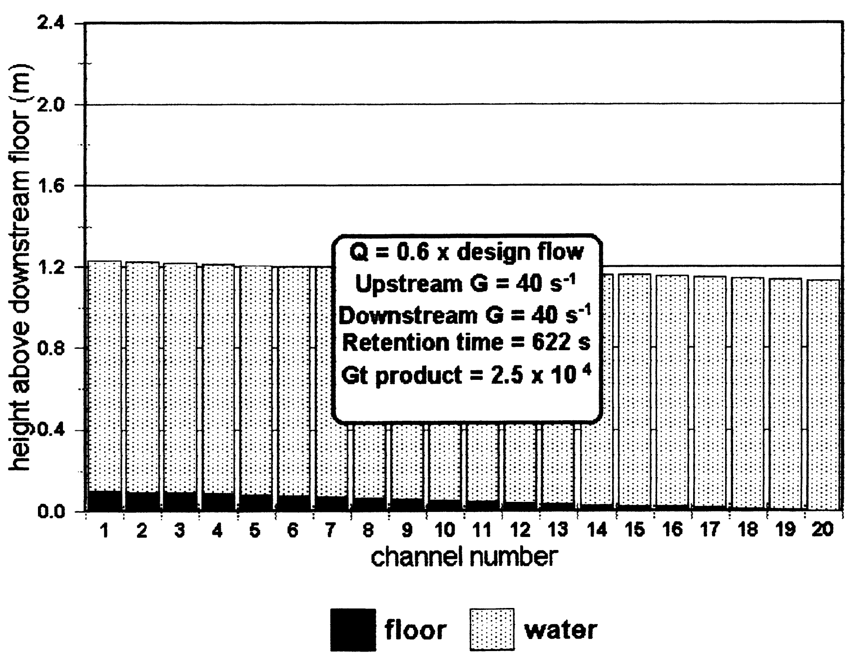

Fig. 4 Floor level and water level profile for Case C.

are then solved as before. It turns out that the upstream velocity gradient is more than 70/s and the average velocity gradient more than 50/s. By incrementally reducing the assumed downstream velocity gradient, an average velocity gradient of 40/s is eventually attained. The values in Table 5 reflect such a solution and the floor and water profiles are shown in Fig. 5.

Case E—increasing the velocity gradient

Another common criticism against hydraulic flocculators is that they do not allow operators to adjust the velocity gradient if warranted by raw water quality changes. Case E will deal with the situation where the velocity gradient has to be increased to 60/s for the flocculator designed in Case A.

Calculations proceed in the usual way from the downstream flow depth (assuming a downstream velocity gradient of 60/s) to conditions at the upstream end. The results are shown in Table 5 and the floor and water profiles are shown in Fig. 6.

DISCUSSION

The two-stage design procedure demonstrated here highlights the great importance of proper water depth and floor slope

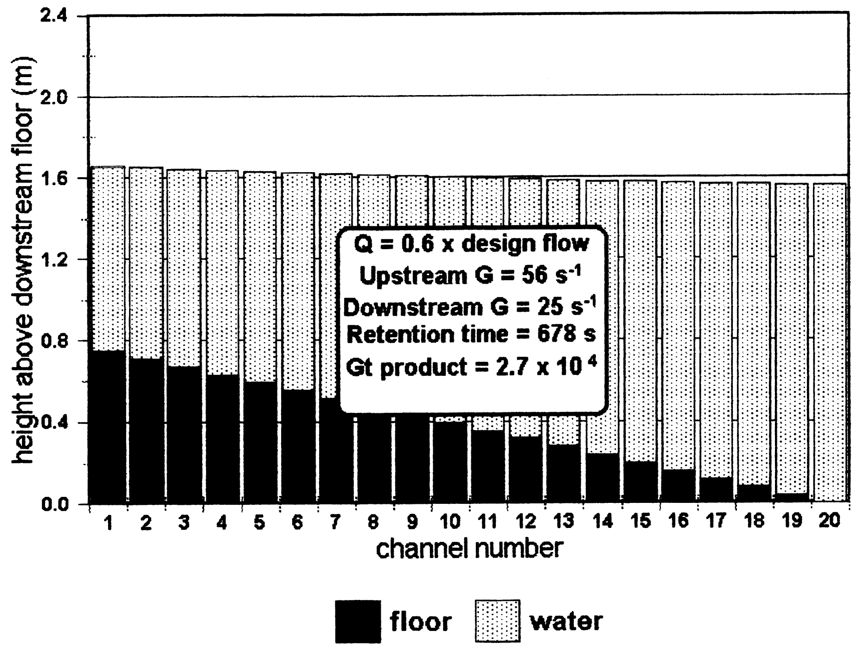

Fig. 5 Floor level and water level profile for Case D.

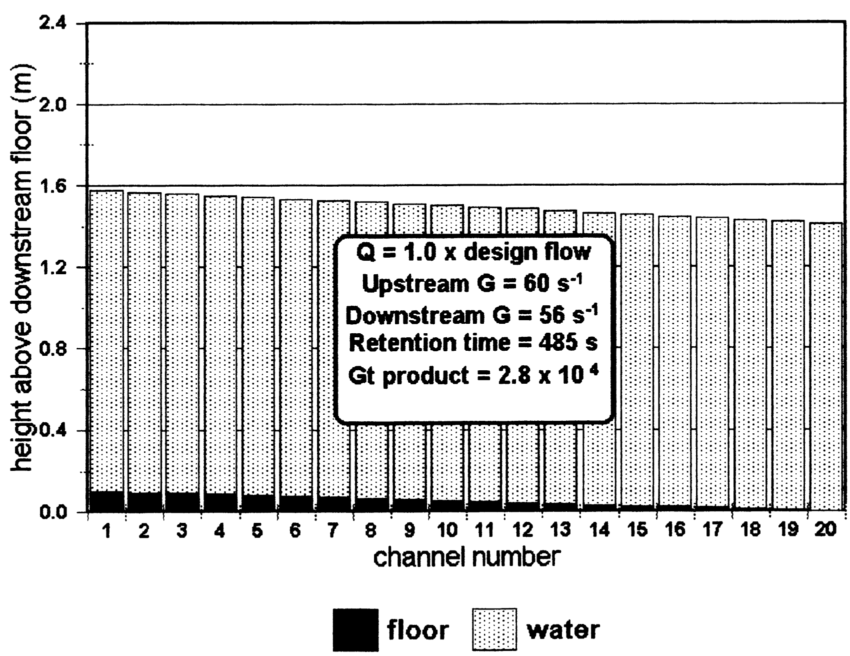

Fig. 6 Floor level and water level profile for Case E.

control. The same horizontal layout, only approximately sized for the average flocculation conditions, could be manipulated through water depth and floor slope to satisfy a wide range of flocculation requirements for different flow rates. In design practice, the design is often considered to be complete once the horizontal layout is done. It is clearly necessary for the designer to pay detailed attention to anticipated flow regimes and flocculation scenarios, and determine the water depths and floor slope accordingly. Moreover, these calculations should be summarised as charts from which operators can simply read the flow depth required to obtain the desired flocculation conditions, to prevent repetitive, error-prone calculations.

The maximum water depths will be encountered when (a) the flows are highest and (b) the average velocity gradients are lowest. Likewise, the minimum water depths will be encountered when (a) the flows are lowest and (b) the average velocity gradient is highest. These two conditions should be used to determine the maximum water level fluctuation, or control band.

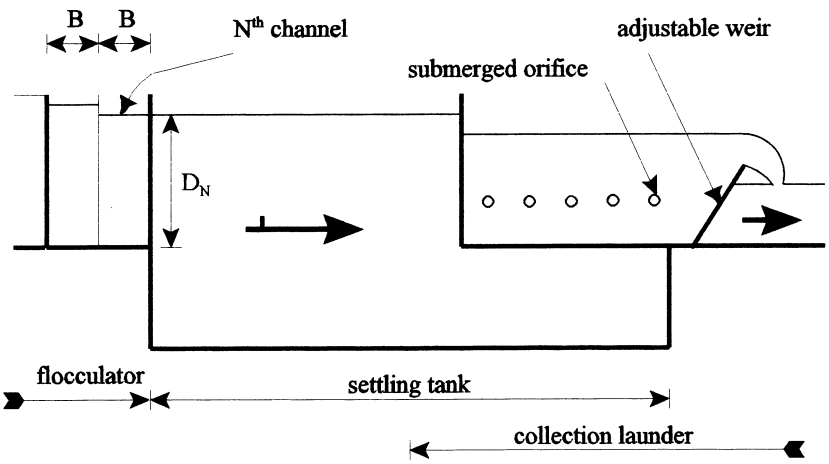

Fig. 7 Schematic section through a part of a treatment plant showing an arrangement where an adjustable weir downstream of the settling tank can be used to control the downstream water depth in a hydraulic flocculator.

Tapered flocculation in hydraulic flocculators is often approximated by providing multiple flocculator sections, each with its own horizontal layout, to obtain a step-wise reduction in velocity gradient as the water flows through the flocculator. To prevent excessive floor slopes, this may still be the best solution when steeply tapering velocity gradients are required. In these cases, a seamless taper in velocity gradient can be obtained by still providing a modest floor slope in each section.

CONCLUSIONS

1 The key variables for hydraulic flocculator design were identified, and practical design ranges for these were established from the literature, a survey of South African treatment plants and fundamental process considerations.

2 Design equations were developed to obtain a horizontal flocculator layout where all the variables are kept within practical range—the first step of the proposed design procedure. During this step, a constant water depth and zero floor slope are assumed.

3 Further equations were developed to determine the exact floor slope and water depths required for the desired flocculation conditions—the second and final step of the proposed design procedure.

4 The proposed procedure was demonstrated with five different flocculation scenarios, all using the same horizontal flocculator layout.

5 It is clear that hydraulic flocculators, if they are provided with the appropriate floor slope and subject to controllable water depth, provide almost unlimited flexibility in design and operation. This is contrary to the common perception that hydraulic flocculators are inherently inflexible.

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