Theory of operation of sludge blanket clarifiers

K. J. IVES

Supplementary notation

F_0 inlet pipe area of Czech slot clarifier
F_1 inlet slot area of Czech slot clarifier
F_2 plan area at top blanket level of Czech slot clarifier
P power dissipated by hydraulic losses
V volume of fluid in which power is dissipated
V_f volume of floc
V_s suspension volume
v_1 inlet velocity in Czech clarifier
Δh_b head loss due to pipe bend
Δh_i head loss at inlet
Δh_d head loss in diffuser
Δh_w head loss due to particle drag
Δp_b pressure drop at pipe bend
Δp_i pressure drop at inlet
Δp_d pressure drop in diffuser
Δp_w pressure drop due to particle drag
ζ_b head loss coefficient for pipe bend
ζ_i head loss coefficient for inlet
ζ_d head loss coefficient for diffuser
ν kinematic viscosity

Dr Igor Tesařík, Reader in Hydraulics and Sanitary Engineering, Technical College of Transport Engineering, Žilina, Czechoslovakia

I have read the Paper, the first theoretical study explaining sludge blanket operation as the orthokinetic flocculation in a concentrated layer of suspended flocs, with much interest. It is shown that the theoretical development leads to important design conclusions.

73. I have performed several experiments with models of clarifiers and observed and measured the respective values on the prototype. The aim of this contribution is to make clear some hydraulic aspects of orthokinetic flocculation in the hydraulically fluidized layer of flocs.

74. It is assumed that the orthokinetic flocculation is intensified by the turbulence in the sludge blanket zone and connected with the head loss. The energy dissipation depends on the shape and inlet form of the vessel and on the physical properties and concentration of the floc. The following example illustrates the calculation of the head loss in the sludge blanket clarifier of Fig. 4.

75. Head losses in the sludge blanket chamber are as follows (Fig. 5):

Head loss in sharp bend

$$\Delta h_b = \zeta_b \frac{v_1^2}{2g}, \qquad (37)$$

Paper published: *Proc. Instn civ. Engrs*, 1968, **39** (Feb.) 243–260.

in which $\zeta_b \approx 1{\cdot}5$ = the loss coefficient at a sharp 90° bend

$v_1 = 0{\cdot}05$ m/s = the velocity in the inlet

$g = 9{\cdot}81$ m/s^2 = the gravity acceleration.

$$\Delta h_b = 1{\cdot}5\frac{25\times10^{-4}}{19{\cdot}62} = 1{\cdot}91\times10^{-4} \text{ m water} = 0{\cdot}191 \text{ mm } (0{\cdot}00751 \text{ in.) water}$$

$$\Delta p_b = 1{\cdot}91 \text{ N/sq. m} = 3{\cdot}99\times10^{-2} \text{ lbf/sq. ft}$$

Inlet head loss Δh_i

Assume $F_0 \gg F_1$;

$$\Delta h_i = \zeta_i \frac{v_1^2}{2g} \qquad (38)$$

in which $\zeta_i = 0{\cdot}5$ = the loss coefficient at an abrupt contraction

$v_1 = 0{\cdot}05$ m/s = the velocity in the inlet

$g = 9{\cdot}81$ m/s^2 = the gravity acceleration.

$$\Delta h_i = 0{\cdot}5\frac{25\times10^{-4}}{19{\cdot}62} = 0{\cdot}637\times10^{-4} \text{ m water} = 0{\cdot}064 \text{ mm } (0{\cdot}00252 \text{ in.) water}$$

$$\Delta p_i = 0{\cdot}64 \text{ N/sq. m} = 1{\cdot}34\times10^{-2} \text{ lbf/sq. ft}$$

Diffuser head loss Δh_d

Assume the diffuser angle $\alpha = 60°$, $F_2 \gg F_1$;

$$\Delta h_d = \zeta_d \frac{v_1^2}{2g} \qquad (39)$$

in which $\zeta_d = 0{\cdot}72$ = the loss coefficient in the diffuser

$v_1 = 0{\cdot}05$ m/s = the velocity in the inlet

$g = 9{\cdot}81$ m/s^2 = the gravity acceleration.

$$\Delta h_d = 0{\cdot}72\frac{25\times10^{-4}}{19{\cdot}62} = 0{\cdot}916\times10^{-4} \text{ m water} = 0{\cdot}092 \text{ mm } (0{\cdot}00362 \text{ in.) water}$$

$$\Delta p_d = 0{\cdot}92 \text{ N/sq. m} = 1{\cdot}925\times10^{-2} \text{ lbf/sq. ft}$$

Weight of the suspended layer

Assume the real fraction concentration of the fluidized layer of flocs to be $C = 0{\cdot}3$ $(0 \leq C \leq 1)$ and approximately equal through the bed depth, the mass density of water $\rho = 1000$ kg/cu. m, the mass density of the floc $\rho_s = 1002{\cdot}5$ kg/cu. m, and the depth of the layer $h = 2{\cdot}5$ m. The head loss is

$$\Delta p_w = gC(\rho_s - \rho)h = 9{\cdot}81\times0{\cdot}3(1002{\cdot}5-1000)2{\cdot}5 = 18{\cdot}4 \text{ N/sq. m} = 38{\cdot}4\times10^{-2} \text{ lbf/sq. ft} \qquad (40)$$

$$\Delta h_w = 1{\cdot}84\times10^{-3} \text{ m } (0{\cdot}0724 \text{ in.) water.}$$

Total loss of head Δh_t

Turbulence losses (equations (37)–(39))	= 0·347 mm	= 0·0137 in. water
Drag loss	= 1·84 mm	= 0·0724 in. water
Total Δh_t	= 2·19 mm	= 0·0861 in. water

The mean velocity gradient $G = \sqrt{\left(\frac{P}{\mu V}\right)}$, $\qquad (41)$

in which P is the output in N/m per s

μ is the dynamic viscosity in N/s per sq. m

V is the volume in cu. m.

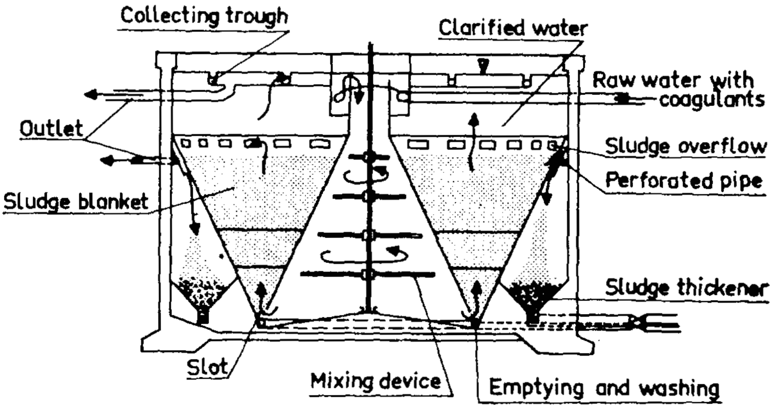

Fig. 4. Sludge blanket clarifier Královopolská Srojírna, Brno

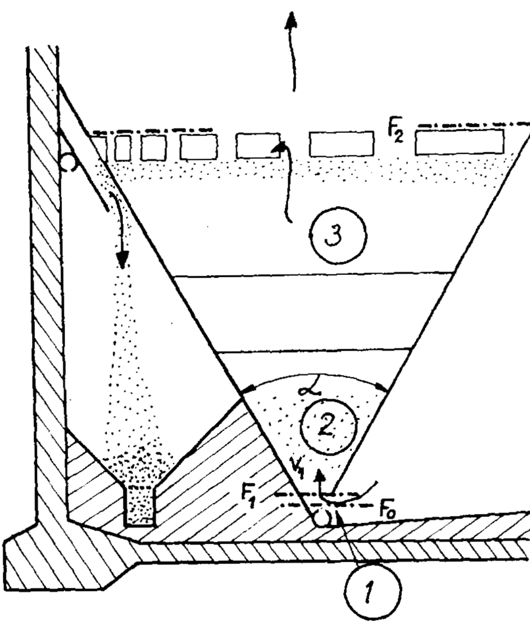

Fig. 5. Losses in sludge blanket zone: (1) sharp bend; (2) inlet; (3) diffuser

The output P is connected with the loss of head

$$P = \rho g \Delta h_t Q, \qquad (42)$$

in which Q is the discharge in cu. m/s.

Introducing equation (42) into equation (41)

$$G = \sqrt{\left(\frac{\Delta h_t g}{\nu t}\right)} \qquad (43)$$

in which t is the retention period in s.
Assume $\Delta h_t = 2{\cdot}2 \times 10^{-3}$ m water, $g = 9{\cdot}81$ m/s^2, $\nu = 10^{-6}$ sq. m/s (20°C), $t = 1800$ s (30 min)

$$G = \sqrt{\left(\frac{2{\cdot}2 \times 10^{-3} \times 9{\cdot}81}{10^{-6} \times 1{\cdot}8 \times 10^3}\right)} = 3{\cdot}46 \text{ s}$$

Camp's number is

$$Ca = G \times t = 3{\cdot}46 \times 1800 = 6225.$$

76. The calculated Camp's number $Ca = 6225$ is lower than the optimal value for flocculation chambers (between 10^4 and 10^5). Nevertheless at temperatures above 15°C and turbidity of raw water above 50 ppm the operation of the clarifier described is good even without mechanical mixing in the flocculation chamber. This result may be explained by the improving action of the concentrated floc layer on orthokinetic flocculation. At temperatures below 15°C and turbidity of raw water below 10 ppm the capacity of the clarifier sinks to about 60% of the nominal value. Almost full capacity is then achieved by adding about 25 ppm of bentonite. Chlorinated ferrous sulphate serves as the primary coagulant in both cases.

77. The calculation shows that in this clarifier the energy dissipation due to 'turbulence' is about five times less in comparison with that due to 'drag' on particles. To achieve a mechanical similarity to a sludge blanket operation the geometric arrangement of the model is of some importance. The condition of mechanical similarity is accomplished with identical heights of the sludge blanket zone and an identical relation of the slot area F_1 to the total cross section F_2 in the model and prototype

$$F_1 : F_2 = 0{\cdot}03.$$

78. Equations (37)–(40) yield then approximately the same head losses in the model and in the prototype and it is expected that the result of the orthokinetic coagulation will be almost the same.

Mr R. W. G. Clerke, Manchester Corporation Waterworks

The Author may be interested in the special features incorporated in the 34 mgd Arnfield Sedimentation Plant of the Manchester Corporation Water Undertaking, the main points of which are as follows.

80. The plant was designed in 1958 on the basis of pilot plant experiments begun in 1954, constructed during 1959/61, and commissioned in 1962.

81. The plant consists of 16 upward-flow sedimentation tanks, each 126 ft 4 in. long by 25 ft wide. The bottom of each tank consists of 20 troughs each 6 ft wide with 60° side slopes. Each trough is fed with pre-flocculated water through an 8 in. horizontal bus pipe and four 3 in. drop pipes spaced at 6 ft centres, terminating 12 in. above the trough bottom. The layout is such that each pair of tanks can handle 4¼ mgd or a surface area rating of approximately 25 gph/sq. ft. The overall depth of the tanks is only 11 ft 6 in., the overall water depth being 9 ft 6 in., including the

trough depth of 4 ft 9 in. The tanks have an integral flat roof to prevent blanket disturbance by wind.

82. Control of the sludge blanket is effected by concentrators constructed by cross walls at the ends of five of the troughs in each tank. The concentrators are 6 ft square by 8 ft 6 in. deep, including 60° slope hopper bottoms, and are capped by precast sills 6 in. higher than the trough sills. There are no inlet pipes to the concentrators, continuous sludge entry being effected from three sides.

83. The concentrators are sized to hold three days' output of sludge, and a third of the capacity is bled once every 24 h, resulting in a three-day retention in the concentrator with an increase of from 0·1%, for normal blanket sludge, to 1·0% solids content.

84. The plant was constructed within part of an existing horizontal flow sedimentation tank and the experimental work indicated the use of such shallow tanks and consequent economy in constructional costs. Similarly the method of sludge concentration based on experimental work reduces the quantity of liquid to be handled during sludge processing, and simplification of the processing procedure and plant.

85. Accepting the use of external flocculation, which experiments in a 6 ft dia. hopper bottom tank showed to be essential even with coagulant aids, the Arnfield plant appears to support many points made in the Author's conclusions.

Mr E. J. Wilcock, Waterworks Project Manager, The Permutit Co.

I read with much interest the Paper by Professor Ives from the point of view of designing sludge blanket clarifiers which have to be constructed and operated in the field.

87. There are many difficulties in translating fairly any small-scale experimental and pilot investigations into full-scale practice. Over the years we have been successful in increasing the efficiency of our design considerably and obtaining increasing performance, although this is essentially a long-term development as it is not practical to construct full-size units purely for experimentation.

88. The first and perhaps most important factor one learns is the need for clean hydraulic design, as the limits of flow rating in the past have been largely due to uneven distribution and upflow patterns.

89. As flow ratings increase, it becomes increasingly necessary to subject hydraulic design to the chemical requirements of the treatment, and although the mathematical analysis indicates the ratings that should be achieved in practice it does not fully consider the chemical aspects of the process. It assumes that the chemical conditions are correct and that the chemical reaction is completed before the water, plus its treatment chemicals, enters the system. Following directly from this, it is assumed that in the sludge blanket zone one is dealing with particles of a fixed size which aggregate into larger particles of fixed size.

90. In a clarifier designed on these principles, so that the hydraulics conform to the chemical requirements, the sludge particles are continually undergoing a chemical/physical change during which the ratio of diameter to density is also changing. Many workers in this field recognize this process, which is generally called 'aging', and it is a factor which is fundamental to the design and operation of upflow sludge blanket tanks.

91. Nevertheless, there is much in Professor Ives's Paper which justifies concepts on which practical design may be based, although it is not agreed that the concentration of sludge is greatest at the top of the blanket in a fully fluidized system. Bond illustrates areas of different concentration at various flow rates with a surface concentration lower than anywhere else in the system. Should the concentration of sludge be highest at the surface of the blanket, particularly if the walls of the vessel above the sludge blanket are vertical, the condition would be unstable. One of the difficulties of comparing Ives's work with that of Bond is that whereas Ives

used a purely conical vessel, that of Bond has a sludge weir with a vertical section above the blanket.

92. In conclusion thanks are due to Professor Ives for the work he is doing, not only in the field of sludge blanket clarification, but also in filtration.

Mr R. W. Aitken, Paterson Candy International Ltd

It is impossible to separate the task of the physical chemist from that of the engineer in considering the controlling factors involved in the formation and subsequent separation of solids precipitated from water.

94. In a vertical flow sludge blanket tank, the inlet velocity is of primary importance. This was discovered by Griffiths[23] in 1934 when he altered what was basically a desilting tank with inlet arrangements designed to cause the minimum disturbance within the tank, by extending the inlet pipe downwards to a point some 2 ft above the bottom, and increased the inlet velocity to approximately 2 ft/s.

95. The Author's example of a vertical flow tank envisages a zone extending 17·5 ft above the apex in which there is no pre-formed floc. In fact, circulating eddy currents produced by the incoming velocity result in mixing, and the sludge blanket has no lower limit but extends virtually to the bottom of the tank.[24]

96. Orthokinetic flocculation begins almost immediately the water enters the tank, which does not support the conclusions drawn by the Author in §§ 63 and 65.

97. Early contact with pre-formed sludge avoids extensive nucleation, i.e. the formation of a precipitate from molecular dimensions. The mixing effect also provides rapid dilution of the supersaturated solution. Both these factors lead to the formation of a denser and tougher precipitate.[25]

98. The energy introduced with the incoming water must be dissipated before the separation zone is reached at the top of the blanket. This is effected by the internal friction or apparent viscosity of the slurry contained in the blanket. Before a blanket is formed, the distribution of velocities in the tank bears no relation to the pattern which prevails after the blanket is established and is the main reason why the addition of a weighting material such as Fullers earth can be useful when starting up with a water containing little or no suspended matter.

99. It is not clear whether the Author would class the dissipation of inlet velocity as energy losses due to turbulent flow or to drag on the suspended floc particles. With an inlet velocity of 3 ft/s the velocity energy in the incoming water is equivalent to 0·141 ft head of water of 8·8 lb/cu. ft. Assuming a contact time in the sludge blanket of 30 min, this would give a value of $4{\cdot}9 \times 10^{-3}$ ft lb/s per cu. ft, which is of the same order as the values of P_D in Table 1. If the inlet velocity energy is regarded as losses due to turbulence, then the conclusion in § 37 is not justified.

100. The value of G mentioned in § 20, namely $100\ s^{-1}$, indicates a wide divergence from the value of $2{\cdot}5\ s^{-1}$ calculated in § 65 but, in fact, the eddy currents induced in the bottom of the tank probably produce values which fall within the limits suggested by Fair and Geyer, namely $25\text{–}100\ s^{-1}$.

101. The slurry weir technique mentioned in § 46 was first used in a vertical flow tank by the Writer in 1939, and has been common practice for many years.

Dr D. G. Miller, The Water Research Association

The Paper makes a commendable attempt to gather together the theories of flocculation and sedimentation to describe the behaviour of a complex fluidized bed reactor. It may be fairly stated that the principal reason for the lack of quantitative data on floc blankets, of which the Author complains, is the problem of analysing the behaviour in such an involved system.

103. The Writer feels that there is a serious gap in the development of the theory presented relating to the separation efficiency of the system. Because this development uses the classical flocculation theory, which assumes that all particles colliding

combine, and because the analysis is carried out on the basis of a single floc size and not a size distribution, no allowance is made for penetration of flocs through the blanket and thus to the filtration stage. The most important aspect of design, therefore, in which the sedimentation tank throughput is optimized together with the filtration stage, is overlooked.

104. Work at the Water Research Association[22] and results published by Tesarik[26] show that the separation efficiency is highly dependent on the upflow velocity. In fact, experiments on Thames Water using aluminium sulphate as coagulant show that with upflow velocities around 20 ft/h as used by the Author, and with blanket depths of 6 ft in a parallel-sided 1 ft dia. column, the separation efficiency is of the order of 50%. Efficiencies for less ideal hydraulic systems, particularly with some of the highly-coloured waters in upland areas, will be lower unless floc tougheners are used to improve the situation.

105. In addition to the effects of upflow velocity and raw water quality, experiments show that chemical dose and pH have a considerable influence on separation efficiency. The Author is simplifying the situation considerably, therefore, in postulating that it is possible to optimize the chemistry for any scheme at the design stage. The jar test is likely to give little guidance in this respect.

106. The problems of size distribution and floc property measurement also influence the usefulness of the settling equations proposed for floc blankets. The Writer has already shown the lack of agreement on the relationships governing the behaviour of suspensions[27] and further evidence has been given by Tesarik.[26] On the basis of this evidence, calculations based on Stokes' law and assuming a single floc diameter are likely to give extremely approximate results.

107. For the above reasons therefore the Writer feels that the theory given falls considerably short of providing a basis on which to design full-scale clarifiers. However, the relationships serve as a useful basis for further discussion and investigation and it is gratifying to see more attention being given to what is a much neglected but important stage of water treatment.

Professor K. J. Ives, University College

Dr Tesarik's analysis of the energy dissipated in the Czechoslovak slot clarifier is interesting in that the bend, contraction and diffuser head losses amount to about one-fifth of the floc blanket drag losses.

109. It is questionable, however, whether they may be added into the total energy dissipated, to compute the mean velocity gradient as Dr Tesarik has done, or considered in relation to the same retention period to calculate the product Gt (Camp no.). The bend and contraction losses occur in highly localized volumes of fluid, with extremely short retention times. If their local Gt values could be calculated, these could then be added to the total Gt for orthokinetic flocculation. However, even this procedure would not be valid if the local G values were so high that flocs would be sheared rather than built up.

110. The calculation of the drag loss in the floc blanket is also open to question. Is it reasonable to assume that the floc blanket concentration will be approximately equal through the depth of the fluidized layer? In the floc blanket zone of the Czechoslovak slot clarifier the ratio $F_1:F_2=0{\cdot}03$ indicates an upflow velocity change of more than 30:1. A uniform concentration would not be expected, from considerations of hindered settling in a fluidized bed. In fact, the purport of the Paper was to show that in an expanding upflow zone it is necessary to deal with conditions in an element layer and arrive at values of G, Gt or GCt by integration. Any approach assuming overall values is not valid.

111. The fact that, in Dr Tesarik's calculation, the value of Gt did not lie in the quoted range of 10^4–10^5 is not surprising. Such values have been taken from

American flocculators where the floc concentration is low, and are not at all comparable with sludge blanket clarifiers. This has been dealt with in §§ 19 and 52 of the Paper.

112. Dr Tesarik claims that similarity is achieved between model and prototype if the sludge blanket zones are of identical height and if the ratios of slot to blanket top area are identical. This appears only to be valid if both model and prototype are parallel-sided vessels. The change in plan section area of an expanding upflow clarifier would demand similar geometry in the model. If the blanket zone height and geometry must be identical, then it follows that, for flocculation and fluidization conditions to be the same, no reduced scale model is valid. This point was made in § 64 of the Paper.

113. Mr Clerke's description of the conversion of a horizontal flow basin to a vertical flow sedimentation tank is interesting, as it indicates an application of the slurry weir principle for blanket level control. It is noted, however, that the upflow rate is only 4 ft/h and that external flocculation is necessary. Undoubtedly, this is because of the limitations imposed by the conversion of an existing structure. If a new plant were to be designed from the beginning it would be undesirable, in the Author's view, to separate the flocculation and sedimentation stages

114. Mr Wilcock's reference to the phenomenon of floc aging is a valid criticism of the theory which neglected physico-chemical changes during orthokinetic flocculation, a point also mentioned by Dr Miller. It is of interest to calculate the mean residence time of the flocs in the blanket so that their age may be established.

115. The floc volume concentration C is equal to V_f/V_s where V_f is the volume of flocs and V_s the suspension volume. In the element layer of Fig. 1 the local volume of floc is δV_f, so

$$C_L = \frac{\delta V_f}{\delta V_s} = \frac{\delta V_f}{(\pi/4)L^2\delta L} \qquad (44)$$

Equation (17) becomes

$$\frac{\delta V_f}{\delta L} = \frac{\pi}{4}L^2\left(\frac{1}{s}-\frac{4Q}{s\pi v_s L^2}\right)^{3/2} \qquad (45)$$

Taking the limit $\delta L \rightarrow 0$, and integrating between L_1 and L_u

$$\int_0^{V_{fu}} dV_f = \int_{L_1}^{L_u} \frac{\pi}{4}L^2\left(\frac{1}{s}-\frac{4Q}{s\pi v_s L^2}\right)^{3/2} dL \qquad (46)$$

This integration gives the total volume of floc in the blanket. In the case of the example given in §§ 52 eq seq., this total volume $V_f = 82{\cdot}8$ cu. ft. At a dosing rate of 100 mg/l alum the floc bleed at equilibrium is $17{\cdot}7 \times 10^3$ l/day, or 26 cu. ft/h (§ 60). So the mean residence time of the flocs, at this dose rate, is $82{\cdot}8/26 = 3{\cdot}2$ h. For the more normal alum dose of 20 mg/l, the mean residence time would be 16 h. This, of course, is a mean residence time: some flocs will remain longer in the blanket and some for a shorter time. However, it indicates that floc age is to be measured in hours, rather than in minutes or days.

116. Bond's observations[24] on concentrations in the floc blanket indicate mixing and backflow due to diffuser flow at the inlet. This has been observed in the sludge blanket clarifier under investigation by the Author, and shows poor control of the tank flow. As was stressed in the Paper, this is a condition to be avoided, so that better operation can be achieved, resulting *inter alia*, in the highest concentration being at the blanket surface.

117. The Author cannot agree that, if the walls of the vessel above the sludge blanket are vertical, the condition would be unstable. There is ample evidence[20–22] that vertical-sided vessels can achieve blanket stability, even at rates considerably higher than normal. The stability of such a fluidized bed is exactly analogous to that of a sand filter fluidized during backwashing, where no instability is evident if the

washwater distribution is uniform. If the floc blanket is allowed to rise into a vertical-sided part of the vessel, its concentration in this part will be uniform because the plan section is not varying with height. Any floc which escapes from the blanket into the clear water above finds itself as a single unhindered particle, and consequently will fall because its settling velocity will be greater than the water upflow velocity. When it falls back into the blanket, it again experiences hindered settling and is in equilibrium with the upflow. Thus, provided that the water does not accelerate in the clear water zone above the blanket, the blanket is inherently self-stabilizing. Uneven flow distribution, or draw-off to the decanting troughs, could cause accelerations, but this would be due to poor flow control, not blanket instability. Tesarik,[26] using potential flow theory, has recently shown that the clear water zone depth should be equal to or greater than half the distance between parallel decanting troughs, to avoid disturbing the blanket by fluid accelerations.

118. Mr Aitken claims that in a vertical flow sludge blanket tank the inlet velocity is of primary importance. This point was specifically investigated by Miller[22] and Mr Aitken is referred to Fig. 10 on p. 244 of Miller's paper, where the effect of variation of inlet velocity is shown to be very small. At upflow ratings of 6 ft/h, which is common practice in the types of tanks with which Griffiths was concerned, Miller's results show no significant variation in performance with inlet velocity. The inlet pipe variation made by Griffiths may well have altered the whole pattern of hydraulic flow in the tank, thus changing its performance. Without more specific information than reference to a private communication within a company it is impossible to judge the validity of Mr Aitken's conclusions.

119. The same comment applies to the statement that the distribution of velocities in the tank is different according to whether a blanket is present or not. The Author is prepared to believe that this is so (but not on the grounds of apparent viscosity of the sludge blanket, which is an arguable concept), but no data appear to be available to support the statement. Consequently, the Author and his colleagues are investigating flow patterns by means of probes in a full-scale tank, both with and without the presence of a sludge blanket.

120. It is agreed that eddy circulation currents will occur at the bottom of the tank, due to diffuser flow, as indicated by Tesarik,[26] and as shown by Bond's concentration measurements,[24] where the inlet flow conditions are not properly controlled. Boundary separation takes place, streaming and recirculation patterns are all present; this has been observed in the hopper bottomed tank currently under investigation by the Author and his colleagues. The result of this uncontrolled inlet condition is that such tanks have a low upflow rating (~ 5 ft/h).

121. Mr Aitken's calculation of power dissipated per unit volume due to inlet velocity assumes that this occurs in the sludge blanket. However, the inlet velocity energy is lost in a fairly localized volume of water in some small interval of time, or the energy persists in a submerged jet or diffuser flow. Consequently, the same comments apply as have been made on Dr Tesarik's discussion.

122. If the energy is dissipated as a submerged jet or diffuser in the tank investigated by the Author and his colleagues (hopper shaped, 20 ft high to top blanket level, and 23 ft square at top blanket level), at its present maximum operating rate of 5 ft/h (0·74 cu. ft/s), and if an inlet velocity of 3 ft/s were obtained, the rate of energy dissipation would be $0{\cdot}74 \times 8{\cdot}8$ ft lbf/s. If this takes place in the tank volume below top blanket level (3500 cu. ft) the power dissipation per unit volume would be $0{\cdot}74 \times 8{\cdot}8/3500$ ft lbf/s per cu. ft. The value of G, at 50°F ($\mu = 2{\cdot}73 \times 10^{-5}$ s/lbf per sq. ft) is then

$$G = \left(\frac{0{\cdot}74 \times 8{\cdot}8}{3500 \times 2{\cdot}73 \times 10^{-5}}\right)^{1/2} \text{s}^{-1}$$
$$= 8{\cdot}3 \text{ s}^{-1}$$

123. If this power dissipation takes place in only the bottom one-third volume of

the tank, then $G = 3^{1/2} \times 8{\cdot}3 = 14{\cdot}4\ s^{-1}$. Both values are still below the range of 25–100 s^{-1}.

124. If the entire tank volume below the top blanket level is involved in this power-dissipation, the retention time will be 3500/0·74 s = 4700 s. The product Gt will be $8{\cdot}3 \times 4700 = 3{\cdot}9 \times 10^4$ within the range $10^4 - 10^5$ suggested by Fair and Geyer. If only the bottom third volume is involved, the average retention time is 4700/3 = 1630 s and Gt is $1{\cdot}3 \times 10^4$. This suggests that the tank with an uncontrolled inlet can act as a flocculator, but the penalty paid for this is the hydraulically poor performance of the tank as a phase separator. Blanket stability is only achieved by holding the flow rate down because of the streaming and eddies.

125. The calculation cannot reasonably be applied to the example in the Paper, for if the inlet were uncontrolled to allow streaming, eddies and recirculation, no blanket could be maintained at the upflow rate of 22 ft/h, and any flocculation calculations would be futile. However, as indicated previously, the whole calculation is subject to considerable doubt due to the uncertainties regarding the volume and time in which the power dissipation takes place.

126. The purport of the Paper was to indicate that with proper control, leading to uniform velocity conditions at any plan section, much higher ratings could be achieved, consistent with good flocculation, floc blanket fluidization and blanket level control. Mr Aitken may be correctly describing the status quo; the Author believes that the situation can be changed for the better.

127. Most vertical flow tanks which the Author has seen have had pocket concentrators for sludge with intermittent flow over the lip. However, it is reassuring to know that the slurry weir is in common practice, as stated by Mr Aitken, since it is an obvious improvement over the pocket concentrator.

128. Close inspection, by the Author, of Stevenson's paper[25] has not revealed the statement made by Mr Aitken. Stevenson's paper dealt with precipitation caused by the reaction of two added chemicals in a mixed reactor. Supersaturation of the insoluble products caused nucleation and particle growth in a solid quasi-crystalline form. It is doubtful if this work is applicable to the hydrolysis of a coagulant with the formation of polymeric species which flocculate through perikinesis and subsequent orthokinesis in a sludge blanket clarifier.

129. Dr Miller is correct in pointing out that the Paper makes many simplifications which may not be justified in practice.

130. With regard to chemical conditions, the assumption that the chemistry of the process was defined was necessary to allow the Paper to concentrate on the hydrodynamic conditions. All too often, if a clarifier fails to function properly it has been assumed that adjustments in the type or magnitude of the chemical dosing will correct the fault, and the engineer abdicates his responsibilities to the chemist. The Author would not wish to reverse the situation completely, but he would at least plead that the engineer should recognize that he has a part to play in the design and operation of a sludge blanket process. Models which relate the chemistry and flocculation-separation conditions, such as Tesarik's and Miller's vertical columns and the defined velocity gradient flocculator-decanter,[26] are useful in this regard. With them it may be possible to obtain the requisite experimental data for the physicochemical and hydrodynamic interactions.

131. The Author stated in § 17 that his assumptions regarding particle sizes were greatly over-simplified, but that a similar result had been reached regarding orthokinetic flocculation even when using multiple particle sizes. If, instead of the simple assumptions of the Author, a size distribution function had been used, this would have raised a number of problems. Firstly, an explicit function would be required in order to make the integrations and other mathematical manipulations of the theory. If so, then what function should be used? Secondly, there would have been the formidable problems of mathematical manipulation. In these, should it be assumed that the size distribution is self-preserving? This would have made the mathe-

matics a little easier, but would be a rather doubtful assumption in view of what little we know about floc growth. Thirdly, in what terms should we deal with the distribution function: by volume, mass, characteristic dimension (e.g., Stokes' diameter)? Finally, would we have any way of checking the results empirically? The Author's Research Assistant is currently engaged on sampling from various levels and plan positions in a practical sludge blanket clarifier to obtain local floc volume concentrations (values of C). This is tedious, and time-consuming as well as being subject to the usual uncertainties about reliability of sampling. To do this, with size distribution analysis (if there is an acceptable technique for flocs), would require an extremely elaborate arrangement of sampling, instrumentation and personnel. Perhaps as our understanding of sludge blanket clarification grows, so more refined theoretical and experimental methods will be justified.

132. The Author feels that Dr Miller has made a most useful point by raising the question of separation efficiency. As he has indicated, the Author has assumed a separation efficiency of 100%, which is an extremely rosy view of sludge blanket clarifiers, to say the least. The separation efficiency is inherently expressed in the criterion GCt. If this criterion is at its optimum value, the separation efficiency will be at its maximum. Departures from the optimum will lead to diminished efficiencies. Equation (34), which is for a conical clarifier (other shaped vessels will have different, although similar, equations), states that GCt is proportional to $Q^{-1/2}$. This indicates that, if all other conditions are kept the same, changing the flow rate will move GCt away from its optimum, with a consequent drop in separation efficiency. In this argument separation efficiency is not simply the ratio of inlet minus outlet turbidity over inlet turbidity, or a similar measure for coagulant cation, but an optimized value, taking into account the clarifier flow rate. For example, a very low flow rate could allow a very low residual (turbidity or cation) in the outlet, but would hardly be efficient. On the other hand, a very high flow rate, while apparently good, could lead to high residuals in the outlet, and so again would not be efficient. Somewhere between lies the optimum operation, or maximum separation efficiency The Author suggests that this separation efficiency should be correlated experimentally with the criterion GCt, so that the optimum can be formed, and the penalties for departure from the optimum can be assessed. He agrees with Dr Miller that the sludge blanket stage could then be viewed in conjunction with a subsequent filtration stage so that an optimization of the two could be carried out. Such optima are difficult to define without adequate mathematical models (although *ad hoc* empirical methods are possible).

133. The Paper represents an initial contribution with regard to a mathematical model of sludge blanket clarification. It is to be hoped that it will be refined and made more useful as our understanding improves.

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