Velocity variations in rectangular sedimentation tanks

by

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Mr J. B. White (Lecturer, University of Manchester Institute of Science and Technology) wrote that the Author had produced a most valuable collection of results on flow patterns in rectangular tanks, covering a wide range of tank proportions. Previous work with tracers had given qualitative information and had allowed approximate velocities to be deduced, but the Author had given a much more precise and detailed picture. Work of this kind applied to contact and delay tanks as well as to sedimentation tanks, and Mr White would like to suggest that the Author should make a complete record of his results accessible to future workers by depositing a detailed report in the Institution or the University Library.

92. In studying the Paper, Mr White had been intrigued by §§ 12-15 and he would like the Author to comment on the conclusions he had drawn from them. The essence of the analysis seemed to be that it produced a means of giving a numerical value to the extent to which velocities varied over cross sections of the tank. The method did not apply solely to sedimentation tanks, but to any flow-through tank. Settling velocity need not have appeared in the argument as it occurred only as v/D which was the same thing as the reciprocal of the nominal detention time. Mr White had been unable to see whether L_0 had any physical meaning or whether it was any more than a convenient and arbitrary quantity defined by the first equation of § 12. In addition he had tried to obtain a physical definition of 'effective flow-through time' and 'time ratio'. It was easy to jump to the conclusion that 'effective flow-through time' was the same thing as the mean flow-through time or the time to the centroid of a flow-through curve, but this could not be so. Where there was continuity of flow without dead pockets,⁸ as seemed to be the case in the Author's tests (and was certainly the case to which the analysis related), mean flow-through time was equal to nominal detention period but the Author's time ratio was frequently much less than one. Mr White had come to the conclusion that Mr Clements' time ratio was really an indirect measure of the *scatter* of the flow-through times of the components of the total flow. Presumably, the second moment (and standard deviation) of the flow-through curve could be expressed as a summation function of f values, though it would be a different function from $\Sigma f/\Sigma f^2$. In other words 'time ratio' and standard deviation of flow-through time were related via two functions of f values and were different ways of measuring the same thing.

93. This implied that there might be a less arbitrary and possibly a more useful way of quantifying the scatter of velocities but did not detract from the essential value of the Author's findings from his model tank.

94. Another aspect of the Author's mathematical analysis which had worried the Writer was that it was based only on consideration of particles of critical settling velocity, all of which had to be removed. Such a design basis was satisfactory for detritus tanks but not for other settling tanks, where one was more concerned with the rate of removal of solid matter from a suspension of mixed sizes of particles. Working on such a basis Mr White had been able to show the Author's finding was more general. For discrete particles of mixed sizes, the rate of removal was unaffected by variations of velocity in depth but was reduced by variations of velocity across the width. The argument, though simple, needed too much space to be

included in this Contribution. The essential difference between the effects of horizontal and vertical variations of velocity on settlement was not surprising; the root cause was that gravity acted vertically. It was fortunate that horizontal variations were easy to minimize whilst vertical ones were inevitable, again through the influence of gravity. The extent to which one's mathematical expectations were borne out in nature, even with a discrete suspension, remained to be seen. In experiments on a model tank fed with a suspension of silica, which would be mentioned in Mr D. M. Thompson's contribution (§ 106), no significant reduction in removal rate had been found when horizontal variations were increased. Of course, neither the Author's critical-particle approach nor the Writer's mixed-suspension approach may have much significance when the suspension was flocculent. Fitch⁹ had shown that for such suspensions, depth (or detention period) was certainly an important factor in quiescent settling. A flocculent suspension might be regarded as one in which the solid matter was accelerating rather than settling at uniform velocity. Analysis of an ideal tank with accelerating particles probably had a much closer connexion with the behaviour of sewage than the analysis using uniformly settling particles and easily showed the importance of depth and detention period.

95. Turning to the Ashover tests, he would like the Author to give more details as to the values tabulated in Tables 7 and 8. Was each value the result of testing a spot sample or was it an average of values from several samples? It spot samples had been used it was evident that significant results could be obtained with much less trouble than one would have expected.

96. Since nothing was known of the actual flow pattern in the Ashover tanks nor was anything known about the settling characteristics of the sewage, the connexion between the model tests and the Ashover tests was rather tenuous. In view of the interesting results obtained at Ashover it was hoped that the Author was encouraged to continue his work so that the connexion between laboratory and field might be strengthened. In some work on circular tanks with which the Writer was concerned, with Civil Engineering Research Association's support, they were finding that the initial concentration of solids had some effect on removal both in settling column tests and in the actual tank, so this factor might need to be kept in view.

97. The Author's work threw further doubt on the value of tracer flow-through tests. These inevitably gave the combined effect of both horizontal and vertical velocity variations. If it was true, for flocculent as well as discrete particles, that vertical variations were immaterial, flow-through tests would seem to have little value. There seemed no alternative to using an actual suspension, so that gravity, which was the important distinguishing factor, was allowed to play its part.

Mr R. P. March (Research Associate, University of Birmingham) wrote that the Author was to be congratulated on publishing in the *Proceedings* work which would allow the practising engineer to design rectangular settling tanks on a more rational basis. The literature was notably lacking in information which could be applied to the design of real settling tanks.

99. The Paper described two sets of experiments. In the model, flow patterns were determined using a mini flow-meter in liquid containing no suspension. For the full-scale experiments in which the liquid to be clarified was raw sewage mixed with recirculated tank effluent no measure of internal velocities had been carried out, although tank settling efficiency had been measured. It was concluded that the full-scale test results supported the model experiments where D/D_1 reduction had given an increase in time ratio and 'would therefore be expected to cause an increase in sedimentation efficiency'. Presumably no experiments had been carried out to correlate internal velocity distributions in the full-scale tanks with settling efficiency although the relation had been shown theoretically. Throughout the Paper it had been assumed that the time ratio was the only parameter controlling settling tank

performance, whereas in fact the settleability and flocculation characteristics must play an important role in full-scale tanks.

100. It would be interesting to know whether flow-through curves had been obtained using the tracer in the model tank. Since velocity meters could not be used in full-scale tanks because of interference to the rotor by solid matter, the use of tracer for velocity determinations was mandatory. It would be useful to know how the Author's 'time ratio' determined by the mini flow-meter compared with 'hydraulic efficiency' defined as $t_{\text{mean}}/t_{\text{theoretical}}$ for a gulp tracer test flow-through curve.

101. Fig. 7 showed two flow patterns observed in the vertical plane using clear water (no density differences) in the model tank. However, in full-scale experiments without baffles it had been shown¹⁰⁻¹² that flow movement was similar to that in the baffled model tank. Did this not invalidate the model tests, or at least make the use of baffles in model tanks rather meaningless when no suspension was used?

102. Further investigations in the full-scale tank would probably show that its internal flow patterns in the vertical plane had been chiefly controlled by influent densities and velocities and horizontal flow patterns by the distribution arrangement at the inlet. In a real settling tank the flow pattern was a summation of the purely hydraulic pattern found in a clear-water model test and of the flow pattern induced by density differences.

103. The Author stated that V/V_e could be assumed to be unity at the outlet weir and that by plotting values of V/V_e for points throughout the tank length the time ratio was represented by the area under the curve. If, at each of these sections, a weir had been inserted then there must have been an improvement in time ratio. In fact, an infinite number of such weirs would give the tank a time ratio of one.

104. This situation corresponded to the infinite number of hypothetical mixing chambers of Thomas and McKee¹³ where, as is shown by Kleinschmidt,⁸ maximum detention was obtained. However, it was obvious that such an arrangement would never be successful as a practical settling tank since it was only concerned with long retention which was not necessarily conducive to high settling efficiency.

105. An aspect of full-scale settling not considered by the Author was flocculation which might be encouraged by density currents. The currents might provide a volume of highly concentrated influent solids with sufficient mixing to encourage particle flocculation.

Mr D. M. Thompson (Research Student, University of Manchester Institute of Science and Technology) wrote that it was interesting to note that the Author had recognized the fact that flow in sedimentation tanks was seldom 'ideal' and had produced a means of dealing with 'non-ideal' flow and some of the consequent problems.

107. It appeared that real flows often had both forward and reverse components in both horizontal and vertical sections. The Author's discussion of the case of flow varying in depth considered only unidirectional flow and the question arose as to whether this treatment could be extended to the more realistic two-directional flow and whether Hazen's principle still held. Such flows had large circulations in the vertical section. Whether there were density currents or surface flows with downward rollers (see Fig. 7), the settling particles could either pass quickly through the tank or be retained in the circulation for a considerable time. The latter phenomenon could produce multiple-peak, flow-through curves of the type reported by Wills.¹⁴

108. Although the general case of flow variable in breadth had been considered it had not been made clear through what mechanism the presence of two-directional flow affected the settling of the design particle. Indeed it was not clear whether the effective settling length was postulated on physical grounds to give the time ratio as an absolute measure of the sedimentation efficiency, or whether it was a definition which led only to a semi-qualitative index which predicted whether an improvement or otherwise might be expected for some change in the tank geometry. In the latter

case $VS^2/\Sigma f$ might better be considered to give an indication of the non-uniformity of the horizontal velocity profile, the worse the non-uniformity the worse the expected settling efficiency. The Author's use of the time ratio in the sewage settling tests seemed to lend itself to the latter approach.

109. The assumption that the deep baffled model produced flow patterns of the type observed by Burgess *et al.*³ was questionable. The scraper gallery at the influent end of the tank and the sloping face under the influent weir¹⁰ must have had some effect on the inflow observed by Burgess. However, the fact that the influent had begun to plunge some distance before the gallery¹⁵ and that it had produced a forward bed flow with a reverse or near stagnant surface flow, indicated that this type of flow was produced not by baffling but by the difference in density between the influent and the fluid in the tank out of which solids had settled. Flows with these characteristics had been observed in a tank with no inlet baffles by Wills¹⁴ and March and Hamlin.¹²

110. Mr Thompson's work at the Institute had also shown that such currents could be produced in a model rectangular tank with a submerged weir inlet. The presence of suspended solids had been shown to modify the clean-water flow patterns, the modification increasing with increasing concentration. The densimetric Froude number had been found to be significant.

111. The model had also been used to investigate the effect of D/D_i on settling performance. One hundred tests were made with influent solid concentrations of 100, 500, 1000 and 1500 mg/l for Reynolds numbers (on the Author's definition), varying from 266 to 2000 for D/D_i ranging from 2 to 16. A further eight tests had been made at Reynolds numbers of 282 and 420 for D/D_i in the range of 4 to 32. In all these tests the performance had been found to depend only upon the discharge and to be independent of D/D_i at any particular discharge. Also the presence of density currents did not affect the tank performance.

112. Although the Author's Reynolds numbers had been higher than the above, and most values of D/D_i in the Writer's work were in a range of time ratios (see Fig. 13) where no great change in the tank performance could be expected, all the tests had consistently showed that the efficiency of sedimentation was independent of D/D_i and model tests which were parallel to the Author's sewage tests (§§ 63–69) had shown that in both series the removals had been the same in both tanks.

113. It might be remarked that the Author's work applied to sewage whereas the Writer's applied to discrete non-flocculent particles, and that this accounted for the differences found. If, however, the Author's work was founded on Hazen's ideas then it might be expected that the Author's theory might fit more satisfactorily to work using a sediment of inert, discrete particles rather than to sewage.

Mr E. J. Hall (Deputy City Engineer, City Council of Johannesburg) wrote that this interesting Paper rightly drew attention to the serious effects of variations in horizontal velocity across the breadth of a horizontal sedimentation tank, a concept similar to that considered by Fitch.¹⁶ Such variations in velocity were susceptible to control, however, as the Author had demonstrated, as they arose largely as a result of poor inlet design.

115. The Author's contention that variations in horizontal velocity in the vertical plane had little effect was not so easily accepted. Variations of velocity in the vertical plane, which must include negative forward velocity, could be shown to have a most detrimental effect. This could be regarded as being more serious, as far as tank performance was concerned, as it was far more difficult to control, being due to the cumulative effects of many factors, notably density currents, which were not easily overcome.

116. The flow in the vertical plane of a horizontal tank had been investigated by many workers. Based on work by Burgess *et al.*³ and Wills and Davis,¹¹ the typical case could be represented in Fig. 22. The flow in the effective length of the tank could be analysed in this case by accepting the simplification that there were two super-

FIG. 22: SIMPLIFICATION OF TYPICAL FLOW

imposed tanks, with identical lengths and breadths; the flow in the upper being in the reverse direction to that in the lower.

117. Using the Author's notation with additions as follows:

Q_r rate of flow in the upper tank

D_a depth of the lower tank

V_a mean horizontal velocity through lower tank

V_r mean horizontal velocity through upper tank

v_r minimum settling velocity of particles completely removed in the lower tank,

and assuming uniform velocity in the vertical plane in both the upper and lower tanks, gave a form of recirculation in which the flow through the upper part of the tank, the recirculation current, was Q_r . In the lower tank the flow was $(Q + Q_r)$.

118. Taking the lower tank, particles would be completely removed if they had a settling velocity greater than or equal to v_r

$$\frac{v_r}{V_a} = \frac{D_a}{L}$$

or

$$v_r = \frac{D_a V_a}{L}$$

but

$$V_a D_a B = Q_r + Q$$

whence

$$D_a = \frac{Q_r + Q}{V_a B}$$

therefore

$$v_r = \frac{Q_r + Q}{BL}$$

Similarly in the ideal tank without recirculation it could be shown that:

$$v = \frac{Q}{BL}$$

whence

$$\frac{v_r}{v} = \frac{Q_r + Q}{Q} = 1 + \frac{Q_r}{Q}$$

This was significant if the value of Q_r was significant. Wills and Davis calculated that Q_r was $1.09Q$ in the experiments conducted on the Coleshill tanks. In that case

$$\frac{v_r}{v} = 1 + \frac{1.09}{1}$$

or

$$v_r = 2.09v$$

which was highly significant.

119. Work by Burgess and Green¹⁰ on the London Northern Outfall works primary sedimentation tanks had indicated a forward velocity along the floor of 7.5 ft/min. The total flow for this tank, which was 75 ft wide, had been 14.8 cu. ft/min per ft width. This quantity would occupy a depth of floor of $14.8/7.5 = 2$ ft approximately. The tank depth was 11 ft so that there would be 9 ft occupied by the recirculation eddy.

120. Equating the velocities of recirculation the flow in the eddy, Q_r in this case, would be

$$\begin{aligned} Q_r &= \frac{9}{2} \times 7.5 \text{ cu. ft/min} \\ &= 33.7 \text{ cu. ft/min.} \end{aligned}$$

Here, therefore,

$$\begin{aligned} v_r &= v \left(1 + \frac{33.7}{14.8} \right) \\ &= 3.25v. \end{aligned}$$

121. A forward velocity of 7.5 ft/min was not incompatible with theory as could be easily demonstrated. The Writer¹⁷ had calculated that a density difference of 0.00009 on either side of a vertical plane in a body of liquid could generate a velocity of 4.55 ft/min. This density was equivalent to a variation of 0.5°C in temperature or a difference of 300 p.p.m. of suspended sewage solids, e.g. sewage with a suspended solids content of 600 p.p.m. entering a tank where the contents had a suspended solids content of 300 p.p.m.

122. Conditions in the upper tank were of no lesser interest. The recirculatory pattern was such that the laminae in the lower tank may be regarded as inverting themselves on entering the upper and *vice versa*. That is, the lowest lamina in the upper tank would become the uppermost in the lower. Consequently, particles which were not removed in the lower tank (those with settling velocity less than v) would not be removed as the repeated inversions would perpetually intervene to ensure their perpetual suspension. These particles were, in fact, subject to eternal mixing. The conditions in the lower tank were those, therefore, which dictated the tank performance.

123. It was of interest to note that the inversion of the laminae in the small eddies associated with turbulence in the vertical plane was exactly similar in theoretical concept to the large-scale recirculatory eddy considered. Vertical eddies, therefore, could be regarded as leading to continuous mixing and were of some significance.

124. It must be stressed that only non-flocculating particles had been considered in this analysis and it should be borne in mind that the flocculating characteristics of sewage were such that the theoretically undesirable mixing occasioned by vertical recirculation could well be extremely beneficial.

Dr D. I. H. Barr (Department of Civil Engineering, University of Strathclyde) wrote that in § 31 a resemblance had been mentioned as between the flow pattern in elevation found with deep baffles in the model tank (Fig. 7(b)) and the flow pattern found by Burgess *et al.*³ (their Fig. 12). In the latter case the flow pattern had been deduced from concentration *versus* time plots at various points in a full-scale tank using a radio-active tracer. Scraper support beams were, in effect, shallow baffles near the inlet.¹⁰

126. Both in the case of the Author's tests and in those of Burgess *et al.* there had been a relatively high velocity of flow on the bed of the tank near the inlet, with a reverse eddy above. In the case of Burgess *et al.* the bottom flow had persisted for a length of about 15 times the depth out of a total length of about 23 times the depth and with shallow outlet baffles. The Author's Fig. 7(b) showed a bottom flow persisting for a length of about 3½ times the depth out of a total length of about nine times the depth and with deep outlet baffles present.

127. Thus the Author had produced in homogeneous water a bottom velocity concentration near the inlet using a deep guiding baffle. The persistence of this bottom velocity concentration had been very much less than that of the full-scale tank where the obstruction to surface flow was minimal.

128. Dr Barr felt that § 31 would be more significant in the following form.

It was found possible to produce a bottom velocity concentration in the test tank, using homogeneous water, by the device of vertical guiding baffles close to the end wall and extending through half the depth of the tank. This velocity concentration, however, did not persist in any way comparably with the 'naturally' occurring velocity concentration found by Burgess *et al.*

129. It appeared to Dr Barr that the Author had, in fact, given further evidence that small density-difference effects were a significant factor in sedimentation tank flow. If, and when, details were given of the occurrence of bottom velocity concentrations in unbaffled model tanks, it would be necessary to revise this opinion.

130. The conclusion to be drawn from this was that § 56 was, in part, misleading. The Author had produced evidence, from theoretical considerations and from tests in full-scale tanks, that useful progress in design could be made in the absence of concern with the fundamental aspects of sedimentation tank flow. Further, that in certain cases the existence of density currents had less influence on sedimentation efficiency than might be supposed. But it was important to bear in mind that there would always be a point where rule-of-thumb design broke down and thus the Author should have stressed the need for fundamental work.

131. Appendix 1 did not appear to be a 'proposal' or a 'suggestion' to be 'put forward', but to be a reiteration of previous proposals. The phrase 'sedimentation tests in models are not often convenient' may well cover a wealth of hard won practical knowledge. If so, the Author should elaborate.

Mr A. J. M. Harrison (Senior Scientific Officer, Hydraulics Research Station, Wallingford) wrote that in § 1 the Author had stated two reasons why turbulence in a tank was generally considered to be harmful to sedimentation. He had omitted to mention a third important reason: the turbulent exchange occurring within the

FIG. 23: SEDIMENT REMOVAL FUNCTION FOR SEDIMENTATION TANKS

fluid. When this took place there was a net movement of sediment in the direction of decreasing concentration, i.e. in an upward direction. Thus the effect of this exchange in a suspension of discrete particles was to retard the rate at which the sediment was removed from the flow.

133. Using the mathematical solution developed and verified experimentally by Dobbins,¹⁸ Camp¹⁹ had evaluated the effect of turbulence on the rate of deposition in a sedimentation tank. The result was presented in Fig. 23, which showed the relationship between the efficiency of removal, η , the Hazen number vL/VD and the turbulence function $vD^{1/6}/Vng^{1/2}$. The nomenclature was that used in the Paper with the following additions:

- η efficiency of removal =

$$\frac{\text{quantity of sediment of a given size trapped}}{\text{quantity of sediment of the same size entering the tank}}$$
- g acceleration due to gravity
- n Manning's roughness.

The abscissa parameter could also be written more generally as $v/1.49\sqrt{\tau/\rho}$ where τ was the mean shear stress on the bed of the tank, and ρ was the density of the fluid.

134. The assumptions made in Camp's solution were:

- (a) there was no scour at the bed of the tank;
- (b) the fluid velocity was the same at every point in the tank;
- (c) the turbulent mixing coefficient, ϵ , was also the same at every point.

The last two assumptions were in fact contradictory, since it was shown in Dobbins' analysis that the third assumption implied a parabolic velocity distribution. However, the Author had demonstrated in §§ 8 and 9 that variations of velocity with depth had no influence on the settling length required. Furthermore, the Writer had obtained good agreement with Camp's theory in experiments with fine sand in a settling tank having large length:width and length:depth ratios.²⁰

135. If sedimentation tanks were designed on the basis of a time ratio of 0.95 and a Hazen number of unity (as the Author suggested in § 90), then Fig. 23 showed that the turbulence function must be greater than about 20 for 100% efficiency of settling. The Writer would like to know whether this condition had been satisfied in the tanks at Ashover. Taking a depth of 10 ft, and a Manning n of 0.013, this meant that the ratio v/V must exceed 1.0, but a fall velocity exceeding a typical forward velocity of 0.01 ft/s would be considered relatively high. For example, if the tank was dealing with unflocculated quartz sediment, a fall velocity of 0.01 ft/s would imply a grain size of 0.063 mm, i.e. a size intermediate between a very fine sand and a coarse silt.

The Author thanked the contributors for their comments and for raising points which needed clarification.

137. It was noted that the discussion indicated a continued interest in velocity variations in a vertical plane and, in certain instances, a reluctance to accept the main emphasis of the Paper, i.e. if scour was avoided velocity variations in a vertical plane had less serious effects on the efficiency of rectangular sedimentation tanks than did velocity variations across the breadth of the tank.

138. Mr White had not only followed through the theoretical argument but had also extended it to a further stage. Although it had seemed convenient to the Author to use velocity and settling length in developing the argument, there was no rigid necessity for this and it was quite feasible to arrive at the same conclusion by another route as suggested by Mr White. On the question of the physical meaning of L_{∞} , raised by both Mr White and Mr Thompson, he felt that the latter's second alternative in § 108 was a fair summary of the position.

139. Regarding the physical definition of time ratio, which had been attempted

in §§ 22–24 of the Paper, some care was needed. The Author felt that time ratio could not be related directly to flow-through curves since it took account of variations in flow-through time on plan only and not in elevation. Here again Mr Thompson's conclusions in § 108 were true. If any attempt were made to relate time ratio and the scatter of flow-through times as suggested by Mr White care would be needed to segregate scatter in elevation from scatter on plan and it was not easy to see how this could be done without velocity measurement.

140. Time ratio could not be an absolute measure of sedimentation efficiency but was an index of the tank's ability, by virtue of its shape and inlet arrangement, to allow flow to pass through it without disturbance to the velocity distribution across the breadth. As such it was, in the Author's opinion, an extremely important factor in the tank's sedimentation efficiency.

141. In reply to Mr March's query, although in the early laboratory experiments some work was done on flow-through curves obtained with tracers in the model, the realization of the importance of time ratio led to the discontinuance of the use of tracers as flow-through time was seen to have no valid relationship to sedimentation efficiency. This last point had been made by Eliassen²¹ and Fitch¹⁶ without apparently finding general agreement. It was emphasized again in § 23 of the Paper and had been taken up by Mr White in § 97.

142. The news of Mr White's extension of the theory to discrete particles of mixed sizes was very welcome and confirmed the doubts which the Author had of the treatment attempted by Fischerström.²

143. As had been suggested by several writers in the discussion the theory would certainly need to be modified where the settling velocity was accelerated by flocculation (which had been specifically excluded). However, another factor which the simplified theory ignored, as rightly pointed out by Mr Harrison, was turbulent mixing which had the effect of hindering settlement. It would not be proper to consider one refinement without the other in any more sophisticated approach.

144. Three writers (Mr White, Mr March and Mr Harrison) had asked for more information about the Ashover tests. There was really little to add to that given in the Paper in which, though briefly summarized, the relevant data had been included. The samples shown in Tables 7 and 8 had been merely single spot samples taken at the end of the 3 h period in each case. It was appreciated that this method was only suitable for straight comparisons. The Author recommended this approach as it had ensured that the initial solids concentration, settleability and flocculation characteristics had been the same in both tanks so that there had been only one major variable in each series. The effect of turbulent mixing was to be considered later. The tests had been performed for a specific purpose only and it was realized that the results did little more than support the laboratory findings in a limited way.

145. It was confirmed that no experiments had been carried out to determine velocity distribution in the Ashover tanks. The Author would not agree that the use of tracer for velocity determinations in full-scale tanks was, as Mr March wrote, 'mandatory'. Using a float technique in other tanks it had been found possible to obtain readings at quite low velocities, sufficient to arrive at values of effective mean velocity on plan and hence the time ratio; this possibility was being exploited. Although the limited field observations carried out so far had shown some interesting variations in velocity distribution in the vertical plane (in particular due to different wind directions) these did not appear to have much influence on tank efficiency and so encouraged the Author to believe that the theory would stand up to field testing. He was in agreement with Mr White that tests on full-scale tanks were necessary and work on this aspect would certainly continue.

146. It was regretted that shortage of time would almost certainly prevent early preparation of the detailed report suggested by Mr White but the idea would be borne in mind.

147. In emphasizing a new point (viz. the importance of time ratio) the Paper had

naturally concentrated on the effects and causes of variations in that factor but it was not true to state, as Mr March had done, that it had been assumed throughout that this was the only parameter controlling settling tank performance. A re-reading of §§ 4 and 56 would confirm that Mr March was in error on this point, and another section of the Paper was specifically devoted to the importance of high velocities near the floor as affecting scour.

148. Turning to the flow patterns in the vertical plane, in which there was a continued interest, the Author recalled that the laboratory tests had shown that vertical eddies were always present, that it was possible to obtain high values of time ratio despite their presence, that the value of time ratio depended mainly on D/D_1 and to a smaller extent on tank shape, and that the same value of time ratio could be obtained with eddies of both the top-flow and bottom-flow type.

149. Mr March had quoted full-scale tests in which the tanks were unbaffled and the pattern was of the bottom-flow type. This was almost certainly due to the density differences which existed between the influent and the main body of tank contents (although wind sometimes produced the same effect). As in the Author's model tests this flow pattern would not affect the time ratio. The results quoted by March and Hamlin¹² showed that increased sedimentation efficiency was obtained with increased depth of flow (i.e. when the inlet weir was submerged considerably). The Author suggested that this phenomenon was due to an increase in time ratio which in turn was largely due to the reduction in D/D_1 ratio at inlet. He would be somewhat surprised if this possibility had not occurred to Mr March although no mention of it was made in his contribution.

150. The suggestion of improvement of time ratio to 1 by insertion of an infinite number of weirs did not appeal (even as a theoretical possibility) to the Author who would settle for a time ratio of 0.95 with a conventional tank having one outlet weir and a well designed inlet.

151. Both Mr Thompson and Dr Barr referred to § 31 in which it had been stated that the flow patterns obtained in the model bore resemblance to those observed in full-scale tanks by other workers. This reference had been to the general similarity of types of eddy, as some justification for the adoption of similar tank Reynolds numbers but both Writers had questioned the comparison in the case of the eddy observed by Burgess *et al.*³ The Author would agree that in full-scale tanks density differences would affect the vertical flow pattern but the effect of the shallow baffle should not be discounted. Bottom flow had been obtained by the Author⁵ in a model with a baffle as shallow as $D/17.8$, far less than the depth of the scum trough which acted as a baffle in the tests described by Burgess *et al.*

152. In some of the Author's model tests the eddy had occupied a much greater proportion of the tank length than that shown in Fig. 7(b), which was for a Shape I pattern. In the next tank of the series (Shape II) for instance, the eddy persisted almost to section F as shown in Fig. 24. However, since none of the models tested had corresponded geometrically to the full-scale tank in question (see § 85) no detailed comparison had been possible, nor should be made.

153. Dr Barr was thus not justified in concluding from the non-geometric comparison he made that a model did not simulate the flow pattern in a real tank. The Author, therefore, could not accept Dr Barr's rewording of § 31 in § 128, while Mr Thompson's remarks in §§ 110 and 111 would be of interest to Dr Barr in view of his comment in § 129.

154. The Author gladly accepted that the inclusion of the word 'efficiency' after sedimentation in § 130, as suggested by Dr Barr, was a useful refinement to § 56 but could not agree that he had been at all misleading. He hoped that fundamental research of all kinds would go on but researchers must be prepared to concede that not all factors investigated would prove to be of equal importance in their effects.

155. The Author did not claim any special originality for some of the points in Appendix 1, although he believed that certainly § 88 could not be said to be a re-

FIG. 24: MEAN FLOW PATTERN OBTAINED FROM VELOCITY MEASUREMENTS

iteration of a previous proposal. He had felt that there was a need for a clear statement of principles on which useful tests in simple sedimentation tank models could be carried out and had set out Appendix 1 in the hope that a fruitful discussion of the principles would ensue.

156. In stating that sedimentation tests in models were not often convenient the Author had in mind that not all engineers had the facilities open to University researchers. Nor was he speaking from his own experience alone, since some of the inconveniences had been overcome in recent tests on model circular tanks; he had been guided in part by a remark in a paper by Dr Barr²² himself that lack of a suitable 'model' suspension might well rule out small-scale tests.

157. It was of real interest to learn that Mr Thompson had obtained bottom flow, due to densimetric effects in an un baffled weir model, similar to that obtained in full-scale tanks by Wills, Hamlin and March. Further it was noted that in the model the clean-water flow patterns had been modified by the suspended solids, the extent of the modification increasing with concentration. This information in a quantitative form would be of great value.

158. Mr Thompson's statement that, in his tests, the presence of the density currents did not affect the tank performance was also of especial interest to the Author.

159. Mr Thompson briefly described tests in which the D/D_1 ratio was varied without effect on the performance of model tanks. Although not in possession of the full data, the Author noted that the tests were not carried out at constant Reynolds number and considered it probable that the explanation was largely contained in two facts mentioned by Mr Thompson himself, together with a third. First, in the case of the 100 tests the range of D/D_1 from 2 to 8 would cause little variation in time ratio (see Fig. 13) even if the flow were turbulent in every case, which was very doubtful with Reynolds numbers as low as 266. Second, in the case of the eight tests in which D/D_1 varied from 4 to 32 the Reynolds numbers were all very low (282–420) so that it was probable that flow was not turbulent and hence large dead spaces would be present as in § 27. Third, the Author was not clear whether Mr Thompson had used the same model sediment throughout but if so this could also have some effect, as it was not easy to assess results if the same sediment were used for the range of Reynolds numbers quoted (see § 89). It was felt that perhaps these three factors together mattered far more than whether the settling particles tested were discrete or flocculating. Work now in hand at Sheffield included velocity measurement and sedimentation tests in model circular tanks with turbulent flow. Though incomplete, the results being obtained seemed to put a relationship between sedimentation efficiency and inlet ratio quite beyond doubt.

160. Both Mr Hall and the Author had attempted a simple presentation of vertical flow patterns but Mr Hall's simplification in Fig. 22 had strayed from fact and appeared to include a basic error which resulted in wrong calculations in §§ 118-120.

161. Velocity measurements at a large number of points showed that there was, as in Figs 7(b) and 14, a gradual change from forward to reverse velocity, not a sudden change near the middle of the eddy. The Author invited comparison between Mr Hall's Fig. 22 and his own Fig. 24. This was obtained from velocity measurements at 336 points in a model (9b) the diagram being based on mean velocities across the tank. At any section through the eddy the velocity distribution throughout the depth would be similar to that for section DD shown in Fig. 24(b). As was visible in a dye test the great majority of the flow passed beneath the eddy but a small part (q) was captured by the eddy and exchanged for an equal part nearer the inlet. Although the exact size of q was not known it was not a gross error to assume that the eddy formed a dead space (Fig. 24(c)) and that one had again the case of a shallow tank with high velocity (Fig. 24(d)) resulting in no loss of efficiency. This was how the Author had viewed the case of vertical two-way flow referred to by Mr Thompson.

162. In fact, because of the transfer of flow between main stream and eddy, at any cross section through the eddy there was a slightly greater depth of flow carrying $Q+q$ (Fig. 24(b)) but consideration of the actual velocity distribution would show that, whatever the value of q , a higher effective forward velocity did not result and so did not increase the value of the settling velocity of particles captured in the way suggested by Mr Hall.

163. If he were to recalculate his expressions on the basis of a velocity distribution such as that shown in Fig. 24 (which the Author believed to be nearer to the true facts) Mr Hall would find that a very big reduction in v_r resulted, due principally to the fact that the mean forward velocity was very much less than the value near the floor. Modifications of this pattern by density effects would, it appeared to the Author, have the effect of reducing q and so could not seriously affect sedimentation efficiency for discrete particles.

164. It should also be remembered that values of Q_r such as those calculated by Wills and Davis from tracer test curves, included the effects of horizontal eddies which were serious and which had already been taken into account in the time-ratio theory.

165. It had been shown in the Paper (Fig. 14) that mean velocities at the tank floor of up to 15 V were obtainable even without density currents, so that the figure of 7.5 ft/min quoted by Mr Hall (and which represented 5.6 V) was not an abnormally high one. Mr Hall's theory would have to deal with values of V_r , both forward and reverse, much greater than in his example if it were to hold for the density and wind-induced currents found in practice. If not severely modified on the lines indicated this would lead one to expect variations of sedimentation efficiency (due to changes in vertical flow patterns) very much greater than the surprisingly small efficiency variations which appeared common in practice due to such changes.

166. The Author thanked Mr Harrison for drawing attention to the omission of specific reference to turbulent mixing which naturally existed in any full-scale tank. Its effects had of course been excluded, together with those of flocculation, in the very simple theory adopted. Since mixing and flocculation had opposite effects on sedimentation they presented formidable problems to researchers attempting to investigate their separate influences. However, it was perhaps the case that unexpected results had sometimes been attributed wrongly to one or other of these causes when they might have been explained more rationally with reference to time-ratio variations.

167. As Mr Harrison pointed out, all Camp's assumptions were not valid for real tanks. Mr Harrison, however, was perhaps rash to assume that an argument employed by the Author to justify the use of an equivalent mean velocity in calculation of settling length could vindicate the adoption of a uniform velocity when computing turbulent exchange within the fluid. The presence of velocity variations in the

vertical plane should surely be taken into account when considering both mixing and scour.

168. Reference to Fig. 23, if Camp's assumptions were accepted, showed that a deep tank would result in a higher sediment-removal function (and therefore, for a given Hazen number, would sometimes produce higher efficiency) than in a shallow tank. In the Ashover tests the first series showed that the shallower tank gave the greater efficiency. Hence the effect of the inlet ratio was perhaps slightly greater than previously considered when turbulent mixing was ignored.

169. Mr Harrison had used Fig. 23 in relation to the Ashover tests but had introduced several assumptions that did not apply. It was not known what the time ratios had been but they would be less than 0.95, which appeared to be a practical maximum. Neither 100% efficiency had been obtained nor was the depth of either tank 10 ft. In the case of Tank B, which was only 2 ft deep, the turbulence function of 20 quoted by Mr Harrison would need to be divided by a factor of 6.5 on this account alone. The settling material had of course, been not grit but organic matter, including a high proportion with very low settling velocity. However, the Ashover tests had been not a design exercise but merely a series of controlled experiments to check a laboratory finding, namely that inlet ratio was a significant factor in tank efficiency under turbulent flow conditions.

170. The Author joined Dr Barr in hoping that fundamental research would continue but hoped too that many more model tests and properly controlled full-scale tests, such as those mentioned by the contributors to the discussion, would be undertaken. All methods of attack would ultimately prove of value to the designer of sedimentation tanks for whom the rule-of-thumb approach had been for far too long a dismal anachronism in a scientific age.

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