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MIXING AND DETENTION TIME DISTRIBUTION IN ACTIVATED SLUDGE TANKS

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ABSTRACT

The interrelationship between mixing characteristics and tracer response curves in activated sludge tanks is explained. In some cases the return sludge cycle has a strong influence on the tracer response curves. Results from tracer tests in the field are hard to interpret because the tracer in the return sludge interferes with the initial tracer. Therefore a special evaluation procedure has to be applied. The paper closes with results from a field tracer test study.

KEYWORDS

Activated sludge process, mixing, tracer tests, detention time distribution, stagnant zones.

1. INTRODUCTION

The manner in which wastewater is introduced into the tank and the mixing characteristics of the aeration tank are important parameters in the activated sludge process. They exert considerable influence upon the concentration of residual polluting matter in the effluent (Gould, 1939) and the sludge settling properties (Chudoba, 1973; Rensink, 1974; Wheeler and Jenkins, 1983). Despite decades of intense discussion about these influences, the actual mixing process was rarely investigated. One reason for this is the difficulty of tracer test evaluation due to the circulation of return sludge. Regardless of whether the input signal was an impulse (one single addition) or a step function (continuous addition), tracer particles recirculated through the return sludge prevented definitive conclusions regarding mixing from being drawn.

By additionally observing the tracer concentrations in parallel basins or in the return sludge, the problem of evaluation caused by recirculating tracer particles can be overcome while preserving at the same time the real influence of the return sludge on the mixing pattern (Bode and Seyfried, 1984). To provide a better understanding of the results discussed in the following article, some basic comments on the mixing process in activated sludge tanks are presented first.

2. THEORETICAL TRACER RESPONSE CURVES (WITHOUT RETURN SLUDGE CYCLE)

Instead of using a statistical distribution of different detention times, one plots in tracer tests the tracer concentration at the reactor outlet as a function of time. In the theoretical border cases of plug flow, complete mixing, and mixed tanks in series (n completely mixed tanks in series) the output tracer response curves in Fig. 1 are obtained. In order to achieve a generally valid form of representation

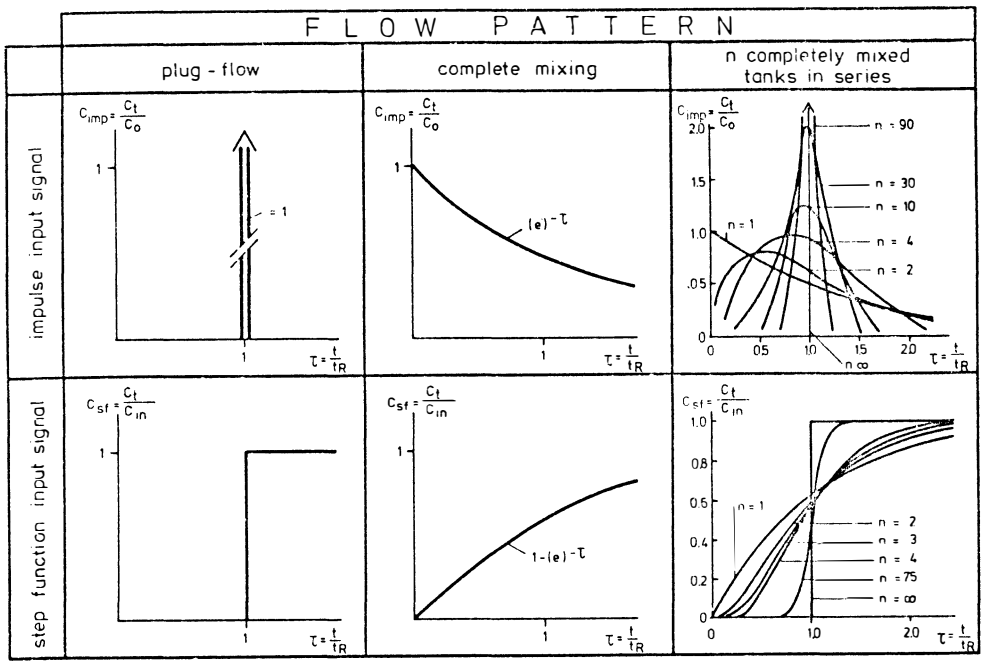

Fig. 1 Output tracer response curves resulting from step function and impulse tracer input signals for different flow patterns

suitable for comparison, effluent concentrations C_t measured at time t are set in proportion either to the calculated initial concentration C_o (in the case of impulse input signals) or to the inflow concentration C_{in} (in the case of step function input signals). The relative effluent concentrations C_{imp} and C_{sf} thus obtained are plotted against the relative detention time $\tau = t/t_R$ (Camp, 1946).

Integration of the tracer response curve produced by an impulse input signal yields a cumulative curve from which the amount of tracer that has flowed out of the system to time τ can be directly obtained. Since the amount of tracer initially in the tank is representative for an influent volume q which has entered at time $\tau = o$, Seyfried (1966, 1974) and Dahlem (1969) chose the ratio $\Delta q/q$ as the ordinate for the cumulative curve, whereby Δq is the component of q still in the tank at time τ (see Fig. 2).

Fig. 1 shows clearly that labelled particles in plug flow do not mix with the tank contents, whereas in complete mixing they are immediately and uniformly distributed over the entire tank contents. The mixing characteristics of tanks in series lie between these two theoretical border cases and approach those of plug flow with increasing tank number n.

3. INFLUENCE OF THE RETURN SLUDGE CYCLE

3.1 FUNDAMENTAL CHANGES IN TRACER RESPONSE CURVES DUE TO PARTIAL RECYCLING OF EFFLUENT (RETURN SLUDGE CYCLE)

If return sludge is fed into the flow of influent wastewater, the velocity of flow increases as given by the continuity equation; the necessary detention time decreases proportionately. This detention time, however, only encompasses one "passage" of the mixed liquor. If one wishes to determine the total time which the wastewater spends in the aeration tank, it has to be taken into account that a portion of the effluent given by $Q_{RS}/(Q_{RS} + Q)$ makes a second "passage". A steadily declining portion of the original volume makes a large number of repeated passages. Whereas the portion of the effluent that flows through the tank only once might have a shorter detention time than if there were no return sludge cycle, summated detention times for the remaining portion are considerably longer than those for no return sludge cycle. The arithmetic mean detention time t_m - relative to all particles - is not, however, altered. (This condition was not always recognized in the literature (Morscheck, H., 1971)). An alteration in the form of the tracer response curve can result, dependent upon the magnitude of the return sludge ratio RSR as well as upon the flow pattern. If one neglects the retention time of the return sludge in the secondary clarifier, the return sludge cycle has the following influence on tracer response curves:

a) PLUG FLOW

In Fig. 2 three cases of cumulative curves of tracer concentrations resulting from impulse input signal illustrate the influence of the return sludge. At time $\tau = o$ a tracer impulse is given to mark the inflowing volume q. In case 1 (RSR = o) the total volume q leaves the tank at time $\tau = 1$.

In case 2 (RSR = 1) the total marked volume reaches the outlet in half the time at t_1, due to the doubled flow $Q + Q_{RS}$ as compared to case 1. However, 50% of the effluent immediately re-enters at the head end of the tank (retention time in the secondary clarifier is neglected) and leaves the tank again at time $t_2 = 1 \cdot \tau$. This bi-

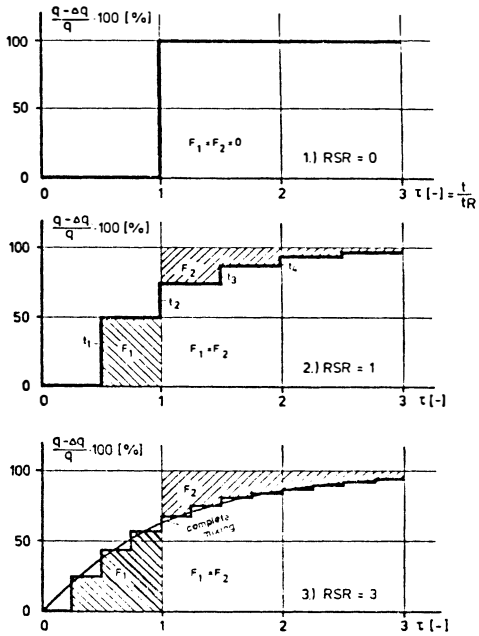

Fig. 2 The cumulative curve of the outflowing tracer at different return sludge ratios in the case of plug flow

section is repeated so that 25% of the original volume leaves the tank for a third time at t_3 = 1,5 τ, 12,5% for a fourth time at t_4, etc.

An increase in the return sludge ratio in a plug flow tank thereby effects a change in the cumulative curve of the tracer response curve. The cumulative curve steadily approaches that of complete mixing. This tendency is even more evident in case 3 where RSR = 3.

b) COMPLETE MIXING

In complete mixing, the return sludge cycle effects no change in the tracer response curve. Just as with plug flow, a component of the effluent, given by the ratio $Q_{RS}/(Q_{RS} + Q)$, immediately re-enters the tank (retention time for secondary clarification is neglected). In a completely mixed tank this component is immediately distributed throughout the entire contents. Since in this type of tank the effluent concentration is identical to that of the contents, the effluent concentration is unaffected by the re-introduction of a portion of the effluent. The completely mixed tank is thereby the only reactor type in which the return sludge cycle does not influence the output tracer response curve.

c) TANKS IN SERIES

In a series of tanks without a return cycle, the tracer response curve varies as a function of the number of tanks n (Fig. 1). Whereas in the border case, n = 1, complete mixing is present, at n = ∞ one is theoretically dealing with plug flow. Accordingly, the return sludge cycle has a varying effect on the tracer response curve and is dependent upon the number of tanks n.

The tracer response curve in a series of many tanks varies more drastically than that in a series of only a few tanks at a given return sludge ratio. This is illustrated by Fig. 3 where the response curves for series of 2 and 4 tanks without a return sludge cycle are compared with those for a return sludge ratio of RSR = 1. The difference is shaded in and is clearly greater for the 4 tanks in series.

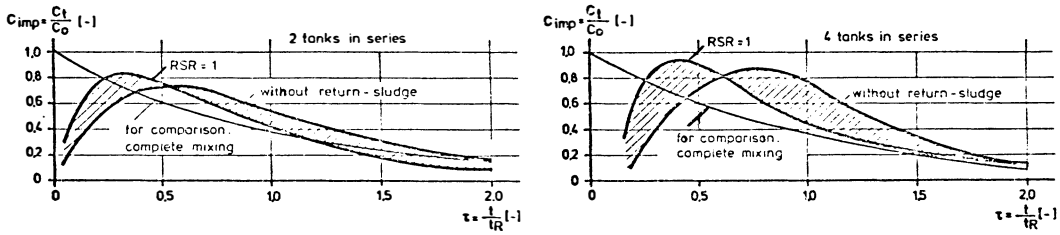

Fig. 3 Influence of the return sludge (RSR = 1) on the output traser response curves for 2 and 4 tanks in series

Fig. 4 shows the tracer response curves for a two tank series at various return sludge ratios.

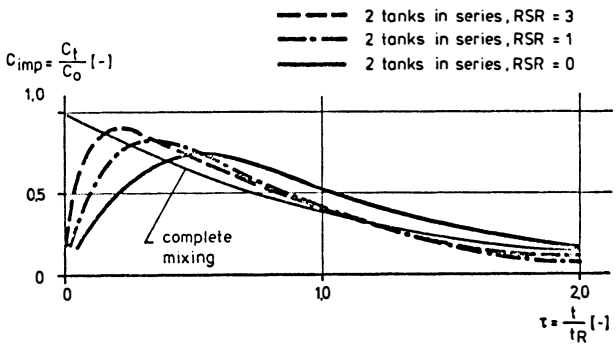

Fig. 4 Influence of the return sludge ratio on the output tracer response curve of two tanks in series

It is evident that by increasing the return sludge ratio, the tracer response curve approaches that of a completely mixed tank.

3.2 IMPAIRMENT OF FIELD MEASUREMENTS DUE TO THE RETURN SLUDGE CYCLE

In field measurements, grab samples from the effluent at a certain time after tracer addition (impulse input signal) contain tracer particles that leave the tank for the first time as well as those from the return sludge. This leads to two further alterations of the tracer response curve other than those described in 3.1. These two additional effects can be roughly described as "time delay due to secondary clarification" and "difficulty of unique correlation between tracer particles and detention time".

The "time delay due to secondary clarification" results from the lag time of the return sludge as it passes through the secondary clarifier and the pipes between the aeration basin and the clarifier. Although this lag time necessarily plays a role in the measurements of the tracer concentration in the effluent of the aeration tank, it is irrelevant for tracer response curves which are intended to describe the mixing characteristics in the aeration tank.

The "difficulty of unique correlation between tracer particles and detention time" becomes evident when one adds up the amounts of all tracer which exit the aeration tank: the sum is greater than the amount of tracer originally introduced. The recirculation of the return sludge leads to the multiple detection of a portion of the tracer. Upon leaving the aeration tank for the first time at t_1, a particular tracer particle is assigned a detention time from the tracer addition at $t_o = 0$ to t_1. The particle re-enters the tank as return sludge and exits for a second time at t_2. Neglecting the fact that the particle was temporarily outside of the aeration tank, a second detention time, t_2-t_1, would be assigned. The detection system, however, is not able to distinguish the particle from others that are leaving the tank for the first time and the particle is incorrectly assigned a detention time from t_o to t_2. The resulting tracer response curve does not reflect the actual mixing processes.

The evaluation method mentioned under 5. is able to eliminate these two effects so that a relevant curve C can be constructed. The real alteration of the tracer response curve described under 3.1 remains unaffected. Due to this real alteration, the possibility of disengaging return sludge pumps during measurements, or of taking other steps which interrupt the return sludge cycle has to be excluded.

4. THE EVALUATION OF MEASURED TRACER RESPONSE CURVES

The desired uniform hydraulic utilization of a tank volume can be impaired by two

factors:

1) By short circuiting flow in which a current of the influent exits the tank very rapidly and in considerably less than the theoretical detention time.
2) By stagnation zones which are only insubstantially involved in the mixing and exchange process of the remainder of the tank.

In short circuiting flow, a portion of the influent flows relatively rapidly into the effluent independent of an otherwise perhaps perfectly normally circulated tank and thereby excludes itself from mixing with the remaining tank contents.

In the evaluation of tracer response curves resulting from measurements in the field, it is rational to compare them with the theoretical response curves for the given tank type (see Fig. 7 (under 6.)). Short circuiting flow can be recognized by the appearance shortly after tracer introduction of tracer concentrations well above the theoretical curve, sometimes fluctuating greatly over short periods.

In addition to a purely optical evaluation of the response curve, it seems desirable to express the complex information contained within the curve as a single parameter or coefficient. This has been attempted with the 50%-value, which defines the point in time at which 50% of all traced particles have left the tank (Dahlem, 1969). This figure, however, has the considerable disadvantage that it can assume identical values for different response curves.

Another figure used for this purpose is the dispersion coefficient (Tomlinson and Chambers, 1979) which, however, in no way investigates the point in time which is to be assigned to the bulk of the tracer as an average exit time but rather describes the deviation from such an average exit time with which the particles leave the tank. Instead of identifying the dispersion coefficient exlusively, it is necessary, for a thorough characterization of the tracer response curve, to incorporate the dispersion coefficient as a supplement to a separate parameter which can describe the average exit time for the bulk of the tracer. It has therefore been occasionally suggested in the literature to establish the ratio between the theoretical detention time $t_R = V/Q$ and the arithmetic mean of the detention times for all traced particles (Ambrose,et al., 1957, Müller-Neuhaus, 1952). This quantity so defined can, however, in measurements over sufficient time periods, only be less than $1 \cdot t_R$ when true dead regions are present. There is no exchange between true dead regions and the remaining tank contents. The circulated tank volume is therefore smaller than assumed. In the field this only occurs with sediments of non-exchangeable substances such as sand. If, however, even the least amount of liquid exchange takes place, then t_m and t_R must be identical within the bounds of experimental error in measurements of sufficient duration.

When in past field measurements, contrary to this finding, values for the ratio t_m/t_R were cited as significantly less than 1, this was due not to dead regions but to stagnation zones and at the same time to premature termination of sample taking. In tracer tests with impulse input signals and the presence of stagnation zones, the extremely low tracer concentrations, detectable even long after tracer addition with sufficiently sensitive measurement methods were neglected.

Despite these problems, in order to be able to make a numerical assertion regarding a measured tracer response curve, the coefficient for comparing mixing characteristics ν is introduced (Fig. 5):

$$\nu = \frac{t^*}{\tau} \; (-) \qquad (1)$$

It holds for t^* that:

$$t^* = \frac{F_1}{F} \cdot t_s + \frac{F_2}{F} \cdot t_R \qquad (2)$$

whereby (see Fig. 5):

F_1 = the amount of tracer having left the tank up to time t_R
F_2 = the amount of tracer having left the tank after time t_R
F = total amount of tracer $F = F_1 + F_2$
t_s = mean detention time for the component of tracer having left the tank up to time t_R.

As the product of the tracer concentration and flow through volume (corresponding to the respective time periods), the areas F represent amounts of tracer having left the tank.

Substitution of Eq. 2 in Eq. 1 yields:

$$\nu = \frac{F_1}{F} \cdot \frac{t_s}{t_R} + \frac{F_2}{F}$$

$$= \frac{1}{F} \left(F_1 \cdot \frac{t_s}{t_R} + F_2\right) \qquad (3)$$

To calculate the parameter t^*, the quantity of particles having left the tank to time t_R is multiplied with the corresponding mean detention time t_s. All particles having left the tank after t_R are assigned the detention time t_R, thereby neutralizing their disproportionately large influence on the mean detention time.

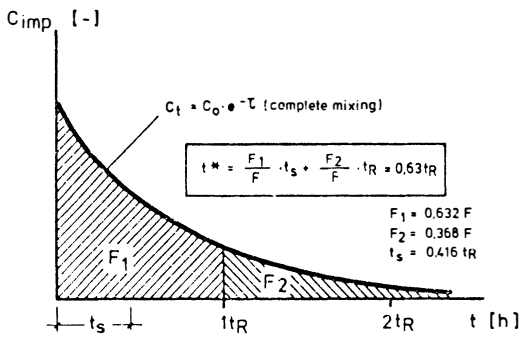

Fig. 5 Determination of t^* in the case of complete mixing

In the case of complete mixing ν becomes 0,63 (Fig. 5) and, in the case of plug flow, 1,0. Whereas values for $\nu > 1$ can neither practically nor theoretically be obtained, it is entirely possible to obtain values less than $\nu = 0{,}63$. These occur in mixing tanks in which stagnation zones are present.

5. DETERMINATION OF THE RELEVANT EFFLUENT CONCENTRATION

Methods for determining the relevant effluent concentration were developed for two different kinds of activated sludge process configurations. The first treats the case of two equally large parallel tanks connected by a common secondary clarifier, the second concerns one line operation plants. Both methods were described in detail by the authors in a previous article (Bode and Seyfried, 1984). They are based on measuring the tracer concentration in the return sludge as well as in the effluent and, in the case of parallel operating lines, also in the effluent of the untraced tank. In the evaluation process of the obtained tracer response curves, a graphical iteration has to be performed which also can be done on a computer. The evaluation results in the relevant effluent tracer response curve C^*, in which the undesired effects of the return sludge are eliminated while the real alteration due to the return sludge remains unaffected (see 3.2).

6. FIELD STUDY

With the help of the methods mentioned, results from seven investigations have been evaluated to date. Of these, the flow measurements from the activated sludge tanks of the municipal treatment plant in Herrenhausen, Hannover, should serve as an example (Bode, 1975).

TEST PARAMETERS

The Herrenhausen municipal treatment plant encompasses two 115 m long tanks (volume = 5,500 m³ ea.), each equipped with 6 pairs of "mammut rotors" for mixing and aeration of contents. Flow direction is aided by guiding walls at the curves (Fig. 6).

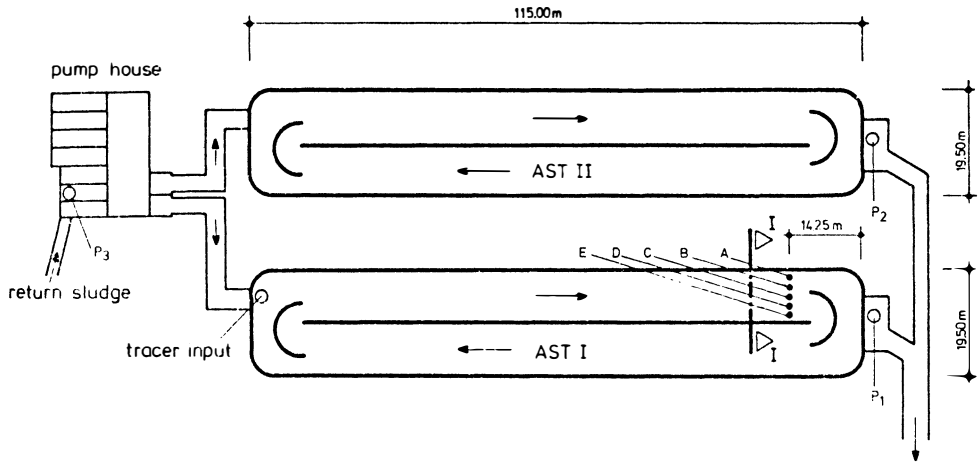

Fig. 6 The activated sludge tanks of the municipal treatment plant Hannover-Herrenhausen with the tracer input and sampling locations

The influent flow of the traced tank I averaged 4,790 m³/h. 70 kg of lithium chloride (dissolved in 130 l water) were added in the space of 6 seconds. Samples were taken at points P_1, P_2 and P_3 (Fig. 6).

The settled sewage in Herrenhausen is advanced by 4 screw pumps into a closed collection channel, from which point it flows underground into the aeration tank. The return sludge is provided with three additional screw pumps. Due to construction technicalities it was not possible to apply the tracer to just one tank through the influent, and since one tank was to remain unmarked in order to observe the influence of the return sludge on the response curve, the tracer was not able to be applied at the common pumping pit. Therefore, tank I was marked directly by introducing the lithium chloride at the point where the mixed liquor enters the tank subsurface. Care was taken that the tracer was not applied too close to the edge of the tank in order to avoid possible stagnation zones. Since the mixed liquor is also transported in closed pipes to the secondary clarifier, samples were taken directly from the effluent weir.

RESULTS

Fig. 7 shows the corrected response curve C^* which was obtained by using additionally the lithium concentration in the second, untraced parallel tank (P_2) and by applying the first method as mentioned under 5. For purpose of comparison, the theoretical response curve for complete mixing in a tank of equal volume is also pre-

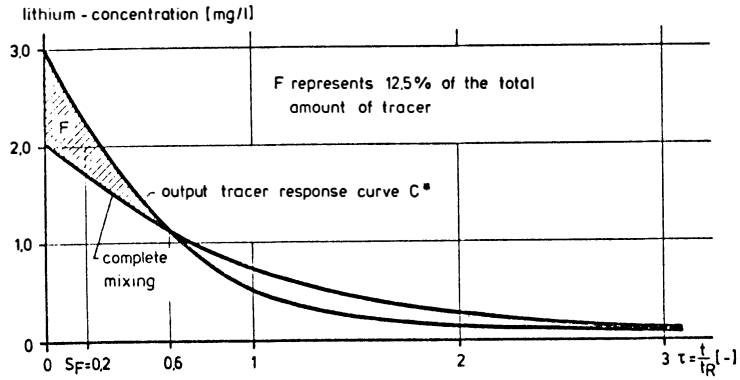

Fig. 7 Corrected output tracer response curve C^* of the tracer study in Hannover-Herrenhausen

sented.

Up to the point $\tau = 0,6$, the concentrations in C^* are greater than the theoretical values. Under complete mixing, 45% of total tracer would have left the tank to this point. In this case, an additional 12,5% of total tracer left the tank in the same amount of time. The initial effluent concentration of C^* was 2,95 mg/l, approx. 45% higher than the theoretical value. Within the theoretical detention time t_R ($\tau = 1$), 74% of the tracer left the tank (with a mean detention time of $t_{m(tR)} = 0,32\ t_R$.) In the same period of time in a completely mixed tank, 63% of the tracer would have left the tank with a mean detention time of $t_{m(tR)} = 0,42\ t_R$ (Fig. 8). These results indicate a relatively great deviation of the mixing characteristics from those of a completely mixed tank. This is supported by the coefficient $\nu = 0,50$, which lies 21% below that of complete mixing and thereby points to the presence of stagnation zones and/or short circuiting flow. Since the wastewater enters the water mass rotating in the tank from the outside and since the outlet is also on the outside of the opposite curve, a certain amount of short circuiting was suspected and consequently confirmed by tracer measurements in the cross section I-I in Fig. 6. The results of these measurements, presented in Fig. 9, represent a "snapshot" of the lithium chloride concentration in the tank cross section 4 minutes after addition of tracer. The arrow P_1 denotes the lithium chloride concentration at the tank outlet and lies in the upper region of curve (a) which represents the cross section distribution. The outflowing tracer concentration is thereby higher than the average concentration for the cross section of flow.

Figs 7 and 9 illustrate that a component of the influent, greater than that for the distribution in a completely mixed tank, appears relatively rapidly in the effluent.

For each particle that flows along the outside of the tank and reaches the outlet before its theoretical time, there is another particle lingering all the longer in the slowly interchanging stagnation zone of the inner region. This is evident from the more horizontal taper of the measured functions as compared to the theoretical functions in Figs 7 and 8. The number of particles that leave the tank only after a multiple of t_R is considerably greater than in a completely mixed tank.

The results make clear that inlet and outlet positions at the opposite curves impair a more uniform and advantageous utilization of the tank volume with respect to the purification process.

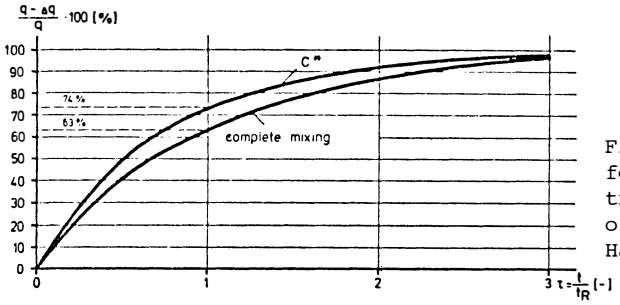

Fig. 8 Cumulative curve for the corrected output tracer response curve C* of the tracer study in Hannover-Herrenhausen

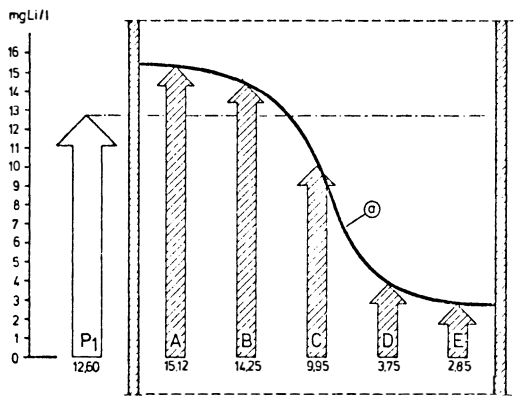

Fig. 9 Cross section I-I of the lithium concentration 4 minutes after tracer addition

7. SUMMARY

The tracer response curves for tanks in plug flow and tanks in series approach the response curves of completely mixed tanks with increasing return sludge ratios RSR.

The degree of hydraulic utilization in aeration tanks can be very precisely determined in field tests employing tracer studies. However, the return sludge cycle, which, due to its influence on mixing characteristics, should not be interrupted during measurements, impedes the acquisition of definitive results considerably; for, in addition to this influence which must be characterized, the return sludge cycle produces invalid relevant concentration distribution for the aeration tank. These invalidities are due to delay of the return sludge in the secondary clarifier on the one hand and multiple detection of tracer particles circulating in the return sludge cycle on the other. Two methods are mentioned with the help of which these invalidities can be characterized and surmounted. One method applies to the case of tanks in parallel flow with common secondary clarification, the other applies to one line operation or several independent parallel lines.

In the field, potentially existing stagnation zones in aeration tanks result in accelerated discharge of a portion of the influent as compared with stagnation-free tanks; this accelerated discharge, however, is compensated for in the mean detention time by the delayed discharge of those particles found in the stagnation zones. In contrast, dead regions result, due to the lack of any liquid interchange whatsoever with the remaining tank contents, in an actual reduction of the mean detention time t_m.

The coefficient ν can serve to characterize the tracer response curve and thereby

the mixing characteristics. ν as a nondimensional quantity yields a mean relative detention time which permits conclusions to be drawn concerning the presence of stagnation zones. The most meaningful application of ν is in comparison with its analogously derived values for the cases of complete mixing and plug flow. In this manner tank forms, aeration devices and mixing devices can be compared and improved.

The results from a field investigation of a tank with rotating flow (mammut rotor tank) demonstrate a clear difference between its tracer response curve and that for a completely mixed tank of equal size. The short circuiting flow apparent there resulted in initial effluent tracer concentrations 45% greater than theoretical value.

NOMENCLATURE

AST	activated sludge tank	(-)
C_{sf}	relative effluent concentration caused by step function input signal $C_{sf} = C_t/C_{in}$	(-)
C_{imp}	relative effluent concentration caused by impulse input signal $C_{im} = C_t/C_o$	(-)
C_t	effluent concentration at the time t	(mg/l)
C_o	theoretical effluent concentration immediately after tracer addition (in the case of complete mixing) ($\hat{=}$ tank concentration)	(mg/l)
C_{in}	inflow concentration of step function input	(mg/l)
C^*	relevant effluent concentration which is significant for the true mixing characteristics of an AST	(mg/l)
n	number of tanks (of equal size)	(-)
P_x	sampling location at x	(-)
q	traced volume of inflow	(m^3)
Δq	rest of q left in the tank	(m^3)
Q	wastewater flow	(m^3/h)
Q_{RS}	flow of return-sludge	(m^3/h)
RSR	return-sludge ratio $RSR = Q_{RS}/Q$	(-)
t	time	(h)
t_m	mean detention time of all tracer particles	(h)
t_R	theoretical mean detention time, $t_R = V/Q$	(h)
t_s	average detention time of all tracer particles which have left before t_R	(h)
t^*	parameter for calculation ν	(h)
V	volume of a tank	(m^3)
τ	relative detention time, $\tau = t/t_R$	(-)
ν	coefficient for comparing mixing characteristics	(-)

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