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ASSESSMENT OF AERATION BASIN PERFORMANCE EFFICIENCY: SAMPLING METHODS AND TANK COVERAGE

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Abstract—A program of oxygen transfer efficiency (OTE) measurements using offgas analysis at the Tillman Water Reclamation Plant (TWRP) in Los Angeles has provided thorough documentation of the performance of fine-pore diffusers in an activated sludge plant. From 1991 to 1993, measurements were made in a uniform pattern that avoided both the ends of the aeration grids and the main pipes along the grid centerlines, which were more likely to be the locations of leaks that could bias the overall average efficiency estimates toward low values. This pattern was chosen in part because of the limited time available during these measurement sessions. When measurements were resumed in 1997 with additional resources, it was decided that several alternatives in sampling should be investigated.

First, to assess the significance of the contributions of areas that previously had been avoided, a much more thorough coverage was performed. Second, a new "longitudinal" sampling scheme was tested, as an alternative to the "transverse" approach that had been used previously. This method not only allows making larger numbers of measurements within a similar time, but provides separate results for the left and right sides of a tank. Measurements were also made with the hood in fixed positions for periods of several hours, to check measurement stability and diurnal variation. In addition to the offgas measurements, data on plant operation were recorded from the field instruments and the control room.

The data show enhanced efficiencies near the upstream and downstream ends of the grids, and in the areas beyond the ends of the grids. This is at least partly the result of known variations in diffuser fouling, resulting from air flows in the distribution pipes. The longitudinal results show an apparent left–right asymmetry, but this turns out to be an artifact, caused by changing air flows during the measurement session, as shown by the control room data. In the fixed position measurements, variability of several percentage points was observed on relatively short time scales. The plant data also corroborated most of the air flux from the offgas instrument.

These observations show the results of going beyond the EPA recommendation to collect offgas from at least 2% of the surface of an aeration basin, particularly when the measurements are planned according to the structure of the air distribution system of the tank. They are steps toward enhancing the importance of OTE monitoring as an input to decisions to clean or repair aeration systems.

Key words—aeration, offgas, oxygen transfer efficiency, OTE diffuser, activated sludge

INTRODUCTION

The oxygen transfer efficiency (OTE) of an aeration basin in an activated sludge wastewater treatment plant is simply the fraction of oxygen that is actually transferred from the air to the basin contents. It is important because airflow is manually or automatically adjusted by feedback from dissolved oxygen (DO) sensors in the tanks in an effort to maintain oxygen transfer in equilibrium with biological consumption. Since the mass of oxygen transferred per unit time is the product of OTE and the mass of oxygen (hence the mass of air) supplied in this time, this gives an inverse proportionality between OTE and air flow (hence blower electricity consumption) for any specified mass transfer rate.

OTE measurements are intended to assess the condition and effectiveness of the aeration system in a basin, but OTE as defined is also sensitive to atmospheric pressure and temperature, and the concentrations of salts, wastes, and DO in the wastewater, all of which are independent from the

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aeration system conditions. Hence, correcting for the departures from standard conditions of all of these except waste concentration gives the standardized OTE parameter, αSOTE, which provides the most uniform basis for comparing aeration efficiencies observed at different times and places. Then the α parameter measures the reduction in OTE caused by wastes. α is defined by the equation $\alpha = \alpha\text{SOTE}/\text{SOTE}$, where SOTE is the standardized clean water OTE, estimated from formulas fitted by the manufacturers to laboratory measurements in clean water.

The results in this paper were obtained at the Tillman Wastewater Reclamation Plant (TWRP), in the San Fernando Valley. Many other large municipal sewage treatment plants have equipment similar to the TWRP, so that the results are relevant beyond the boundaries of the Los Angeles sewer system, and the present successful measurements may provide a starting point for development of programs for use elsewhere.

The measurements were made by the offgas method, which in recent years has been the preferred method for measuring OTE in operating aeration basins, because of its combination of reliability and convenience (Campbell, 1982; Ewing Engineering Company, 1993; Iranpour *et al.*, 1998, 2000a; Redmon *et al.*, 1983). This work is an extension of previous offgas studies such as the evaluation of fine pore diffusers by Allbaugh *et al.* (1985) and Stenstrom and Masutani (1989). The laboratory and theoretical studies of Hwang and Stenstrom (1985), Masutani and Stenstrom (1991) and Newbry (1998) have also been valuable in clarifying aspects of the possible physical and chemical significance of our observations, and we have also found useful comparisons between our results and the recommendations for design parameters in US EPA (1989).

From 1991 to 1993, measurements were made in a uniform pattern that avoided the ends of the grids into which the diffusers on the tank bottoms are grouped. It also avoided the main pipes along the grid centerlines. The samples were taken near one sidewall and halfway across the tank, in the middle of the upstream half and the downstream half of each grid, for a total of four sampling points per grid. This method satisfied the EPA recommendation (ASCE, 1993; US EPA, 1989) for sampling at least 2% of a tank's surface area, since it actually sampled a little more than 3%.

This pattern was adopted because these early measurements focused to a large degree on estimating area- and flow-weighted average αSOTE values for the observed tanks, so that the chosen locations were considered to be the most likely to provide representative results with a small number of samples that would not be biased by, for example, a leak in one of the main air supply pipes. However, beginning in 1997 there were sufficient resources for measurement that minimizing the number of samples became less important.

The experimenters hypothesized that in the changed situation if there were a leak in one of the main air supply pipes, not only could additional measurements prevent the leak from biasing the overall tank efficiency estimate, but detecting it could be valuable for alerting plant management to the need for repair. Thus, the measurements in 1997 and 1998 had a dual purpose of both determining current average tank efficiencies and exploring alternative, more detailed, sampling methods.

MATERIALS AND METHODS

Experimental setup

TWRP is located in the San Fernando Valley, and provides primary, secondary, and tertiary treatment to about 220,000 m^3/day (60 mgd) of wastewater, with a design capacity of 290,000 m^3/day (80 mgd).

The 18 aeration tanks at the plant are operated as single-pass plug-flow reactors, and are in two groups, known as Phase I and Phase II because they were built several years apart. Tanks 1–9 are in Phase I, and were equipped with Sanitaire disc diffusers (9 inches in diameter), while Tanks 10–18 are in Phase II, and were equipped with Aercor dome diffusers (7 inches in diameter). In other respects the two phases are identical. At any given time, some of the tanks are out of service.

Figures 1(a) and 1(b) show the details of a tank, including the grouping of the diffusers into three grids, designated Grids A, B, and C, the spacing of domes, the locations and types of field instruments, etc. The main air distribution manifold in each grid runs across the tank, between sets of lateral pipes that extend equal distances upstream and downstream and are connected at their other ends to the grid peripheral pipes that provide alternative pathways for air if an obstruction occurs. Also, successively smaller numbers of diffusers in Grids A, B, and C provide tapered aeration.

Phase II operates almost independently of Phase I. They both receive primary effluent from a common distribution channel, which is aerated to keep solids from settling on their way from primary treatment, but the clarifiers and RAS systems for the two phases are separate, resulting in the two secondary systems' being biologically isolated from each other. Thus, one phase sometimes suffers foaming, or some other result of an unfavorable bacterial population, that does not occur in the other phase.

The air control systems in two of the Phase II basins differ from the rest, since in Tanks 15 and 16 the valve on the downcomer to each grid is controlled by feedback from a DO probe in that grid. All other tanks have less detailed control, for they are operated in pairs with the valves for all six grids in a pair controlled according to the readings from a DO probe in Grid B of one tank of the pair. For example, the control DO probe for Tanks 13 and 14 is in Tank 14. The only exception to this pairing is that the first tank of the nine in the phase is controlled separately.

The instruments used in the measurements are built by UCLA and the Applied Research Group and use the same principles as the commercially available Ewing Mark V analyzer, but are specialized for convenient offgas measurements from aeration basins. The measurement team promised the plant managers and operators that its work would not interfere in any way with plant operation, and therefore the influent and RAS flows into the tanks were not held steady during the observations.

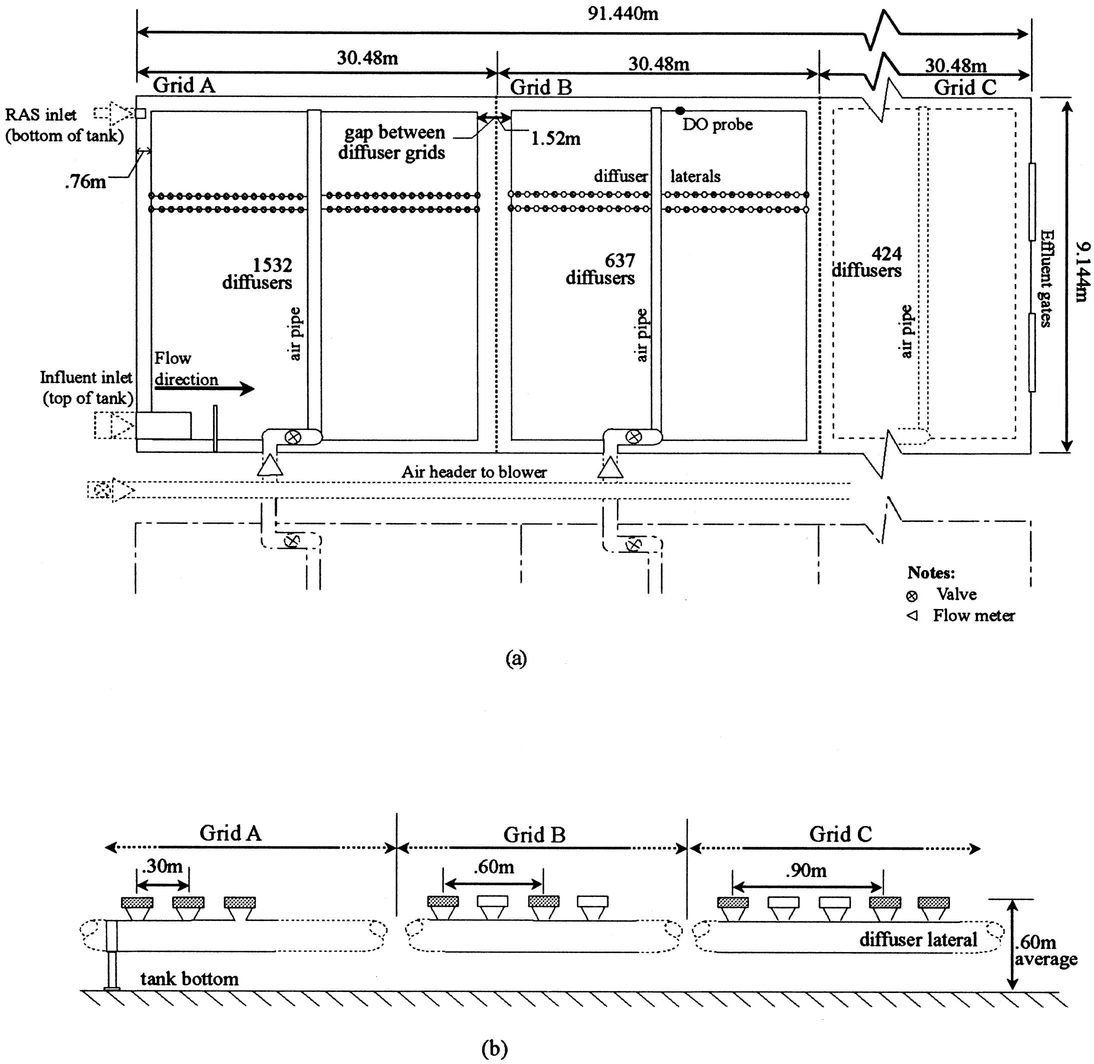


Fig. 1. Plan views of a tank structure in phase II of TWRP: (a) dimensions and components of aeration tanks, (b) dimensions of diffusers in tanks.

Experimental procedure

The offgas measurements are performed in the conventional manner (Campbell, 1982; Ewing Engineering Company, 1993; Redmon and Boyle, 1981; Redmon *et al.*, 1983): offgas is collected by a hood floating on the surface of the tank, and after removal of water vapor and CO_2 from the sample stream the O_2 partial pressure results in a voltage output from a fuel cell. Figure 2 is a schematic of the analyzer structure, showing the components that perform these steps, and the additional tubing and valves that allow calibration readings to be made on the ambient air.

Letting r be the ratio of the fuel cell voltages for the offgas and ambient air, and letting r' be the result of adjusting r to take into account the differing concentrations of inert gases in the offgas and ambient air, the OTE fraction in a local measurement is then $1 - r'$. Hence, contamination of the offgas by ambient air leads to underestimation of the oxygen depletion in the offgas, and thus of OTE. Thus, an important limitation on the speed of offgas measurements is the need for waiting after the hood has

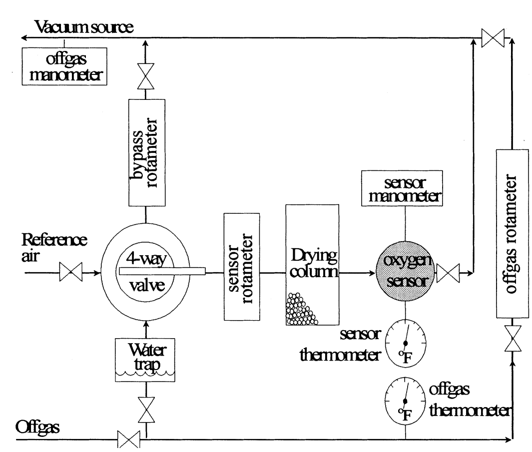


Fig. 2. Plan views of Ewing of OTE analyzer structure.

been moved until sample contamination by ambient air has decreased to a negligible level.

Once the local OTE values are computed, an average OTE weighted by flow and area is computed by the following equation:

$$\overline{\text{OTE}} = \frac{\sum_{i=1}^{m} A_i Q_i \text{OTE}_i}{\sum_{i=1}^{m} A_i Q_i}$$

where i is the hood location sample number, A_i is the area associated with hood location i, Q_i is the air flux associated with hood location i (gas flow rate divided by hood area), OTE_i is the oxygen transfer efficiency measured at hood location i, and, $\overline{\text{OTE}}$ is the overall average OTE.

Correcting for departures from the standard atmospheric pressure and temperature, and for nonzero DO in the wastewater, along with a constant salinity correction for Los Angeles water, gives αSOTE. The instrument provides measurements of ambient air pressure, and a mercury thermometer and a DO meter were used to measure temperature and DO at the point of OTE measurement to convert the raw OTE values into αSOTE according to the following formula:

$$\alpha\text{SOTE} = \frac{\text{OTE} \cdot C^*_{\infty 20}}{(\Omega \beta C^*_{\infty T} - DO)\theta^{T-20}},$$

where $C^*_{\infty 20}$ is the equilibrium DO concentration at 20°C, 760 mm barometric pressure, zero salinity, $C^*_{\infty T}$ is the equilibrium DO concentration at temperature T, 760 mm barometric pressure, zero salinity, Ω is the barometric pressure correction factor, β is the salinity correction factor, $= C^*_{\infty}$ process water/C^*_{∞} clean water, θ is the temperature correction factor (1.024 is ASCE standard), and, T is the water temperature, °C.

As noted in the Introduction, SOTE is the standardized clean water OTE, determined from data or a formula provided by the manufacturer. For the dome diffusers Aercor provided a quadratic formula relating SOTE and a modest range of air fluxes in clean water, deviating only a little from a linear relationship. Then α is computed by dividing αSOTE, determined from the formula above, by SOTE, according to the equation $\alpha = \alpha\text{SOTE/SOTE}$. Since SOTE is derived from experiments under idealized conditions, and depends only on airflux, its only importance for this study is its role in computing α.

Table 1 summarizes the sampling procedures used in the measurements by giving descriptive parameters: sampling strategy, number of sampling locations, number of samples, etc. Before 1997, samples were taken at the positions shown in Fig. 3a. For the recent experiments, the lengths of the tanks were subdivided into a larger number of partitions and measurement stations across the tanks were defined within these partitions. The "gaps and edges" notation in the Tables and the following sections of the text refers to partitions that are close to the upstream and downstream ends of the grids (the "edges") and those that are between the ends of the grids (the "gaps"). However, the time available for the measurements required skipping some of the measurement stations, particularly since measurements at some stations were repeated to check reliability of the instrument readings.

Thus, the "transverse" and "longitudinal" sampling patterns of the recent measurements are less uniform than those previously used, but cover larger percentages of tank surfaces. In the transverse sampling pattern, Fig. 3b, partitions were observed consecutively, moving from the influent end toward the effluent end, with the hood being moved across a tank within each partition for observations at the chosen station or stations. In the longitudinal sampling pattern, Fig. 3c, observations were made along the right side, moving from the influent end to the effluent end as fast as possible, and then returning from the effluent end to the influent making measurements from the left side.

The fixed hood approach left the hood in one position

Table 1. Summary of experimental parameters for tanks in phase II of TWRP: (a) Phase II operation: multiple hood positions, (b) Phase II operations: fixed food position

Date	Tank no.	No. of sample locations		No. of samples		Pattern	Comments
		Grid interiors	Gaps and edges	Grid interiors	Gaps and edges		
(a)							
04/05/91	15	12	–	12	–	Transverse	
	16	12	–	12	–	Transverse	
07/01/92	15	12	–	12	–	Transverse	
	16	12	–	12	–	Transverse	
07/22/93	15	12	–	12	–	Transverse	
	16	12	–	12	–	Transverse	
10/16/97	15	14	4	17	7	Transverse	
10/22/97	16	19	10	20	10	Transverse	
10/23/97	14	24	6	26	6	Transverse	
11/05/97	14	8	8	8	8	Longitudinal	Right side
	14	13	7	13	7	Longitudinal	Left side
02/10/98	11	17	8	25	13	Transverse	
03/04/98	15	19	7	22	7	Transverse	

Date	Tank no.	Sample location	Sample number	Pattern	Comments
(b)					
02/18/98	15	Grid A	28	Fixed	Middle of grid
02/19/98	15	Grid B	18	Fixed	Middle of grid
02/25/98	15	Grid C	30	Fixed	Slightly off center of grid
03/03/98	16	Grid A	26	Fixed	Left leading edge
03/11/98	16	Grid B	32	Fixed	Right center edge
03/12/98	16	Grid C	39	Fixed	Left trailing edge

for a period of several hours and made frequent measurements there. Figure 3d shows the fixed hood positions.

RESULTS

Observations

In addition to high efficiency near the influent end and lower efficiency in the interior of Grid A, the Tank 15 data from 16 October 1997 in Fig. 4 shows a general trend towards higher efficiency along the length of Grid A, an especially high efficiency at the very beginning of Grid B, and irregularly lower efficiency in the interior of Grid B. Owing to a malfunction in the OTE measurement equipment that was not repeated on later days, measurements were not made in Grid C.

The offgas measurements and the corresponding control room data in Fig. 5 are for Tank 16 on 22 October 1997. As in Tank 15, high efficiencies were seen near the influent end, lower efficiencies in Grid A, especially high efficiency at the beginning of Grid B and a repetition of this general pattern of lower efficiencies in the interiors of the grids and a higher efficiency at the very beginning of Grid C. A general trend toward higher efficiencies appears as one goes from Grid A to Grid C, although it is very noisy and is interrupted by the peaks at the beginnings of Grids B and C.

Every 6 min, the control room equipment automatically records influent flow, RAS flow, air flow, and the reading from the control system's DO sensor. For each measurement session in 1997 and 1998, the experiment team has compared the observations with data selected from the control room records at

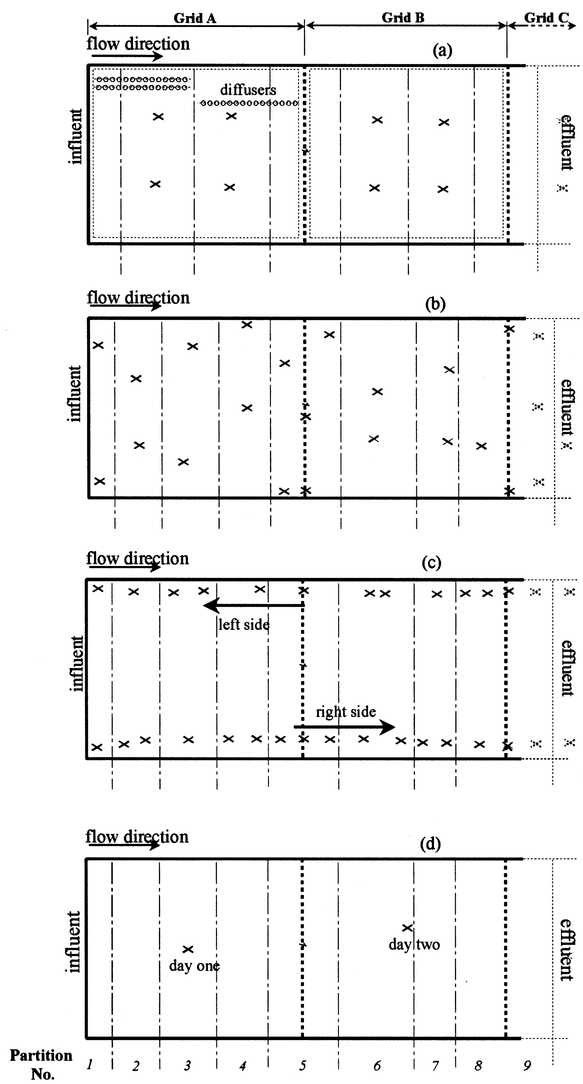
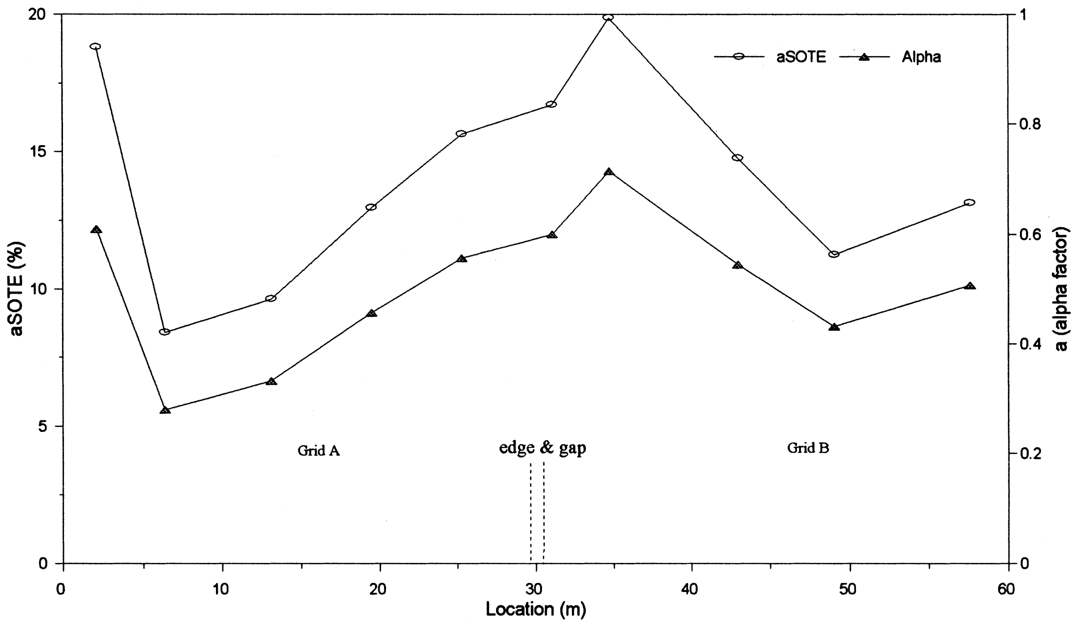
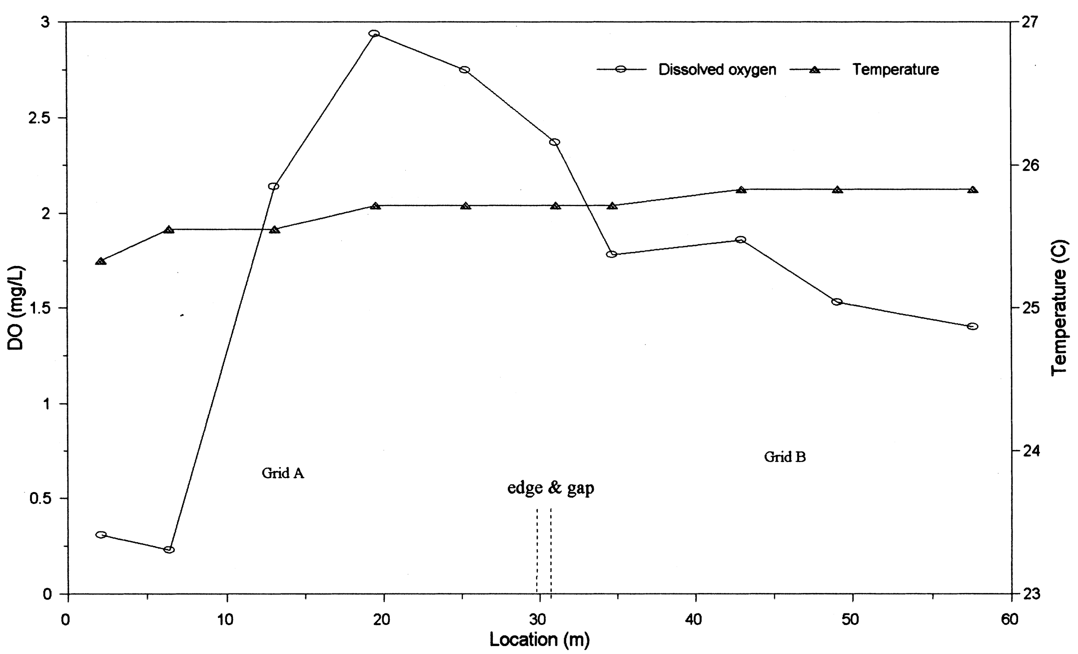


Fig. 3. Sampling layouts applied to different tanks at TWRP: (a) transverse sampling (1991–1994), (b) transverse sampling (1997–1998), (c) longitudinal sampling (1997–1998), (d) stationary sampling (1997–1998).

the times closest to the times of the offgas measurements. The control room data in Fig. 5 are representative of the readings from all the measurement sessions: tank flow and RAS were relatively stable during the period of measurements and DO and air flow generally change in opposite directions, as would be expected from the design of the control system to attempt to maintain a stable DO value. The control room data for 22 October 1997, are displayed in Figs 5c and 5d as an example because this is the first of the measurement sessions in 1997 that covers an entire tank in Phase II, but since little would be added by presenting the corresponding data for the other days, they have been omitted for brevity.



(a)



(b)

Fig. 4. Offgas data for Grids A and B (interiors, gaps, and edges) of Tank 15 at TWRP, 10/16/97 (9:00 am–1.30 pm): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature.

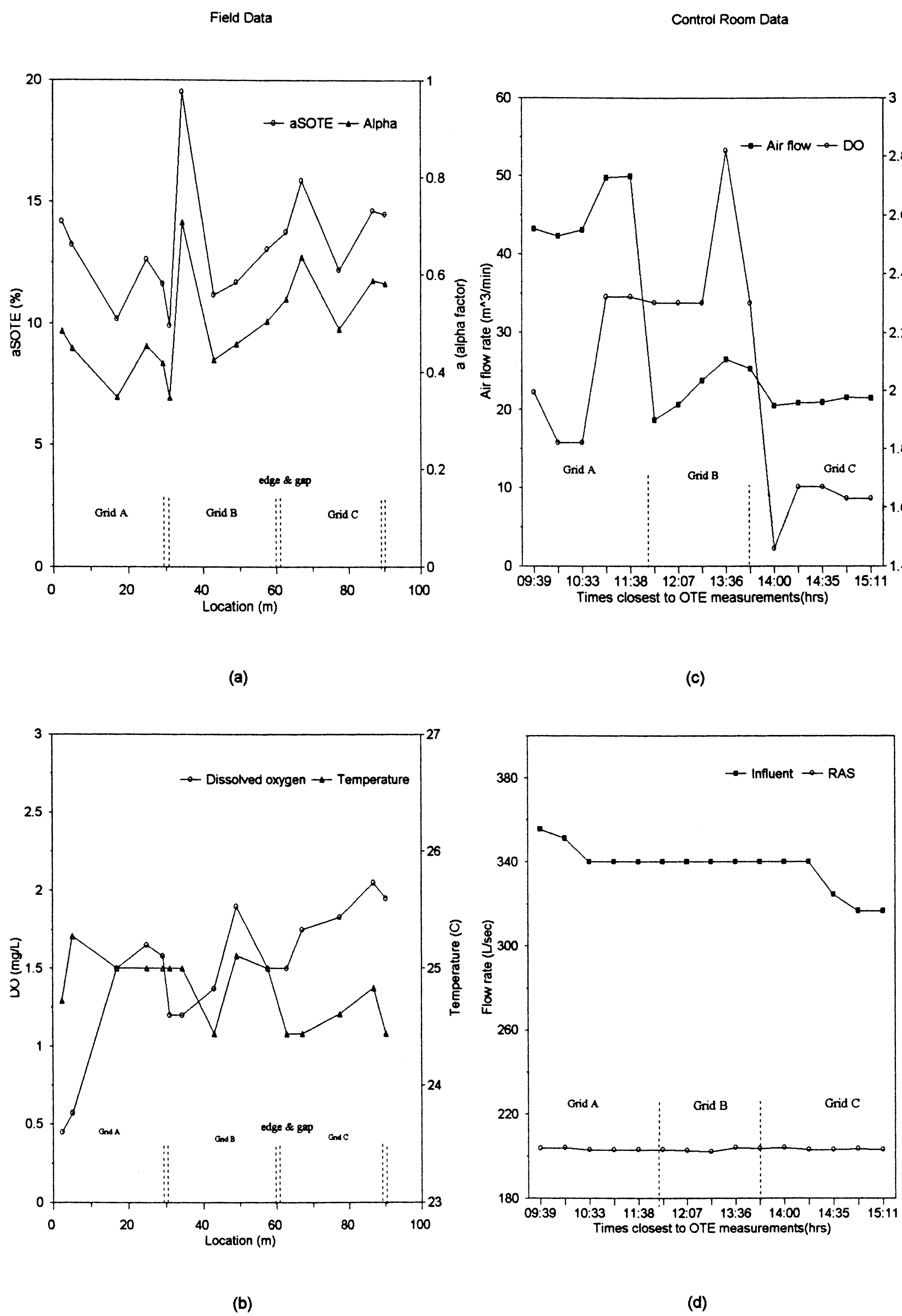


Fig. 5. Offgas data for Grids A, B and C (interiors, gaps, and edges) and Control Room data of Tank 16 at TWRP, 10/22/97 (9:00 am–3.30 pm): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature, (c) air flow rate and dissolved oxygen as a function of time, (d) flow rate and RAS as a function of time.

On 5 November, Tank 14 was sampled using the longitudinal scheme. Figure 6 gives the right side measurements in the same format as in Fig. 4. Likewise, the results for the left side are given in Fig. 7. The left-side results show systematically lower values than the right-side.

For comparison, Fig. 8 shows the αSOTE and α, and DO values from the previous studies of Tanks

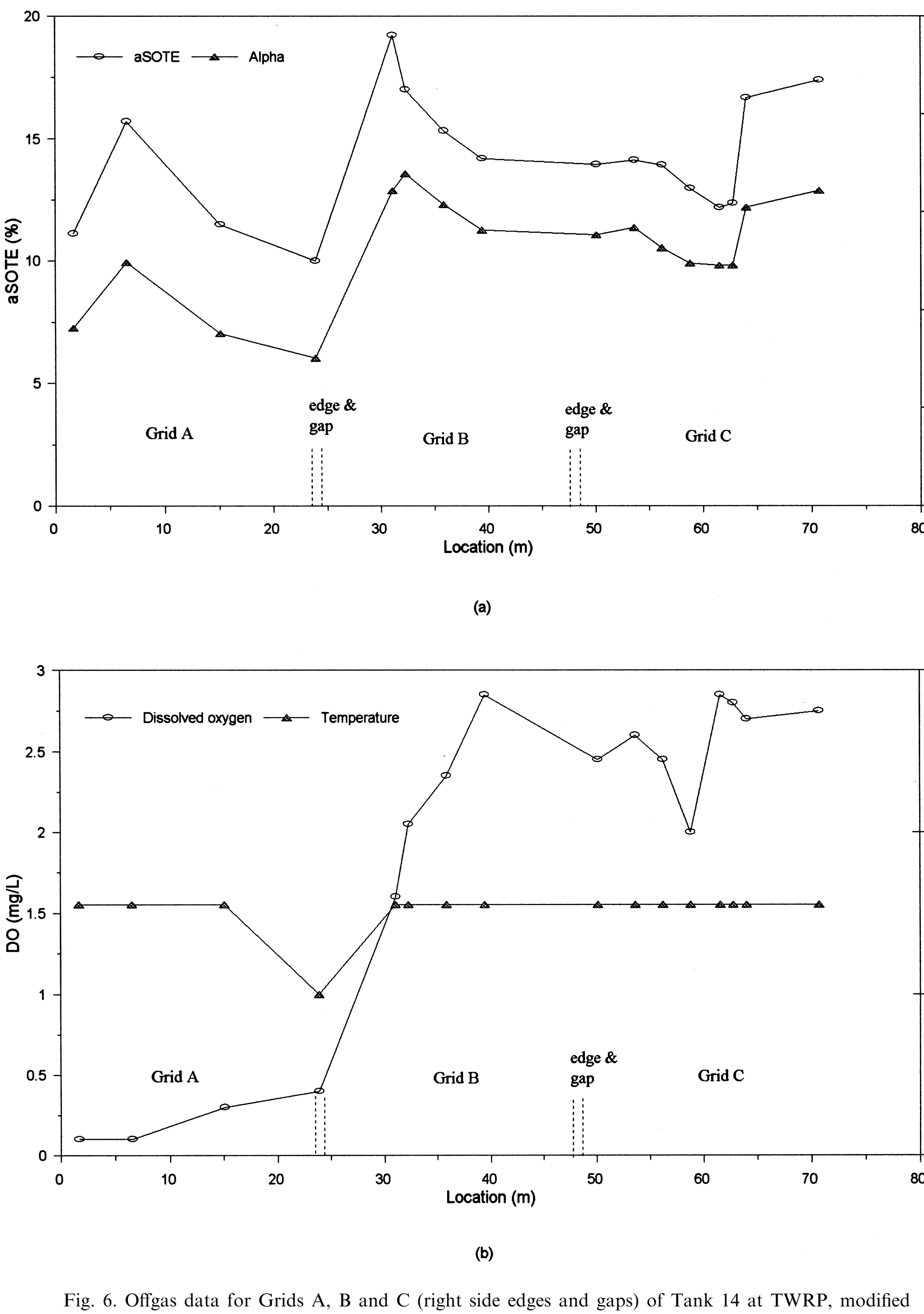


Fig. 6. Offgas data for Grids A, B and C (right side edges and gaps) of Tank 14 at TWRP, modified sampling pattern, 11/05/97 (9:00 am–11.00 am): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature.

15 and 16. It is evident that both the efficiencies and the DO profiles have changed substantially from year to year.

Figure 9 shows the results of measurements at a fixed hood position in Grids A and B of Tank 15, from 18 and 19 February 1998. Figure 10 shows the results of another scan of Tank 15 carried out with the conventional transverse sampling method on 4 March 1998. This Figure is included for comparison with the fixed position data in Fig. 8, and also with Fig. 4.

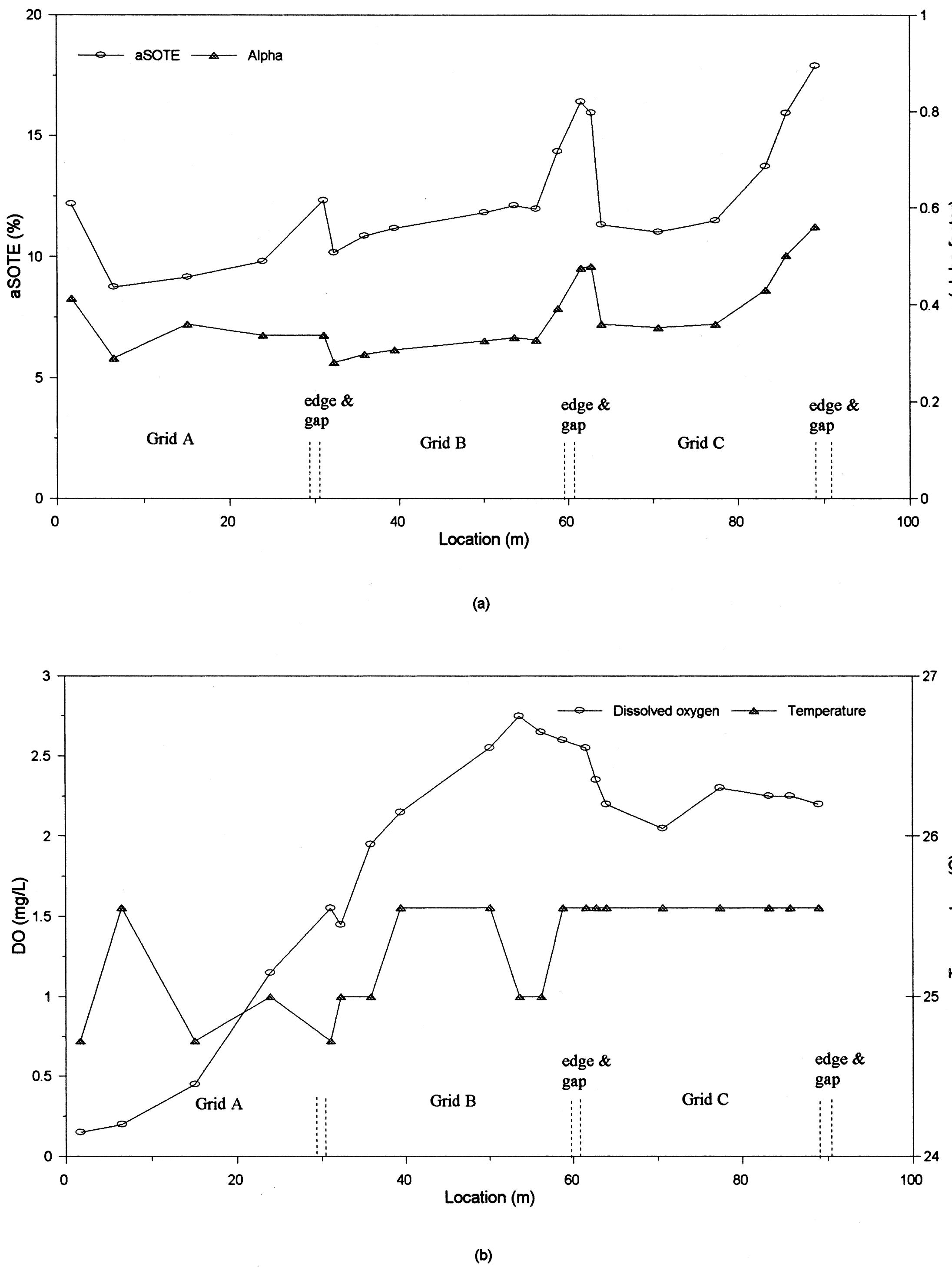


Fig. 7. Offgas data for Grids A, B and C (left side edges and gaps) of Tank 14 at TWRP, modified sampling pattern, 11/05/97 (11:00 am–1.30 pm): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature.

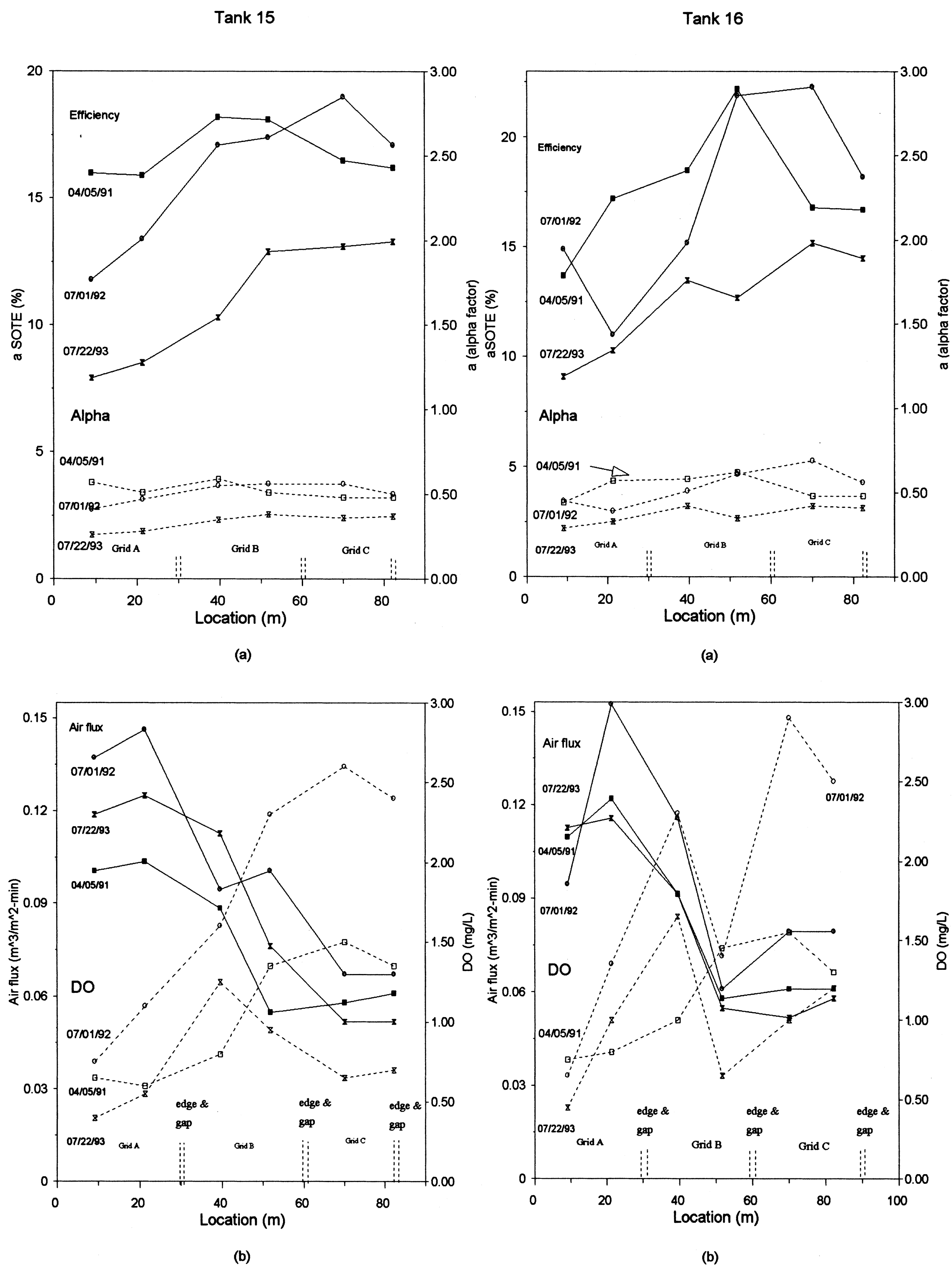


Fig. 8. Offgas data for Grids A, B and C (interior only) of Tank 15 and Tank 16 at TWRP, 04/05/91, 07/01/92 and 07/22/93 (8:00 am–3.30 pm): Tank 15 (a) efficiency and alpha factor, (b) air flux and dissolved oxygen; Tank 16 (a) efficiency and alpha factor, (b) air flux and dissolved oxygen.

Table 2a shows the tank average efficiencies derived by flow and area weighting the individual measurements. The "overall" columns show the averages computed with all the data from the 1997 and 1998 measurements. Area-weighted averages of the new data that omit samples taken in the "gaps and edges" partitions appear in the "grid interior" columns, as do the averages computed from the measurements made in 1991–1993.

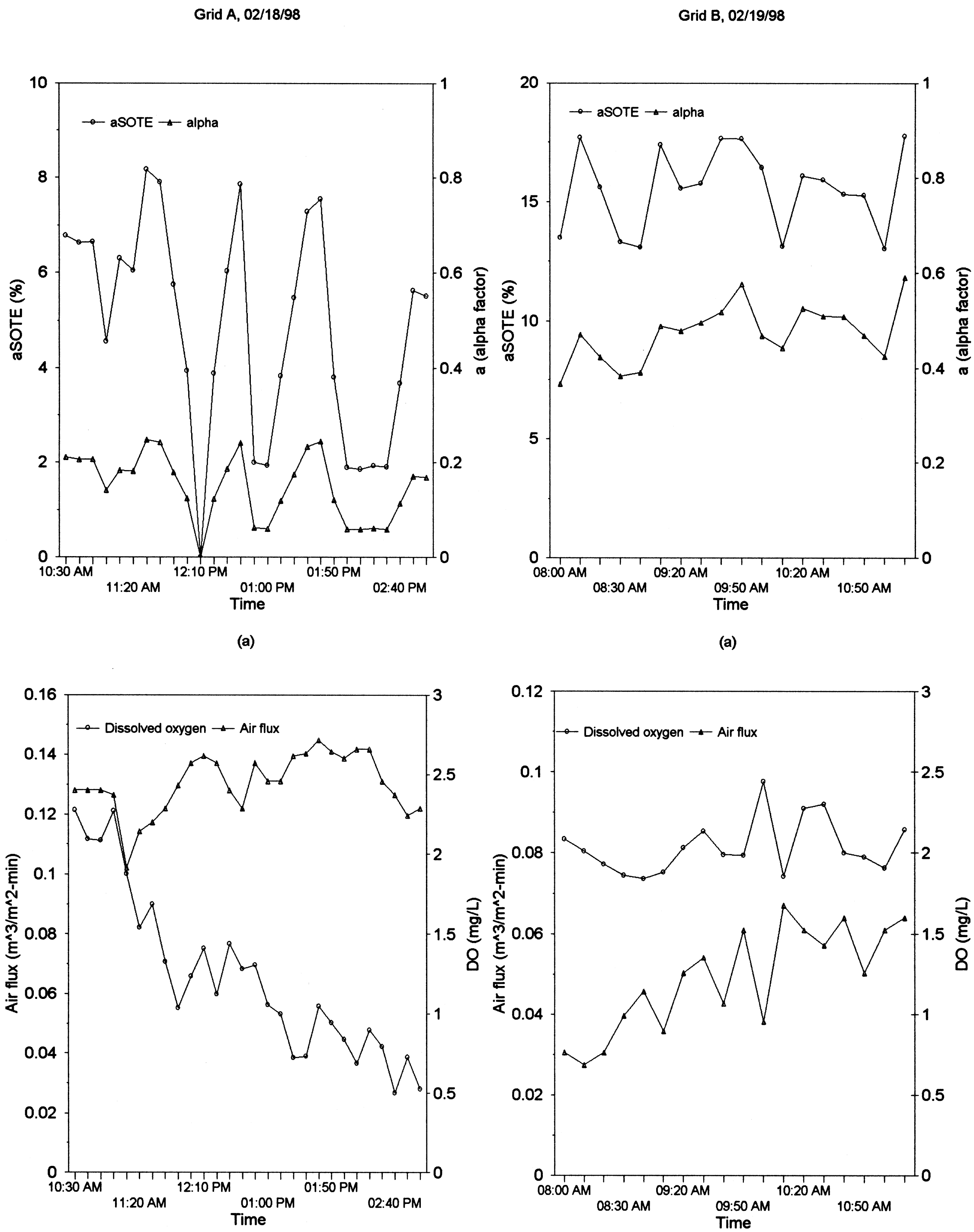
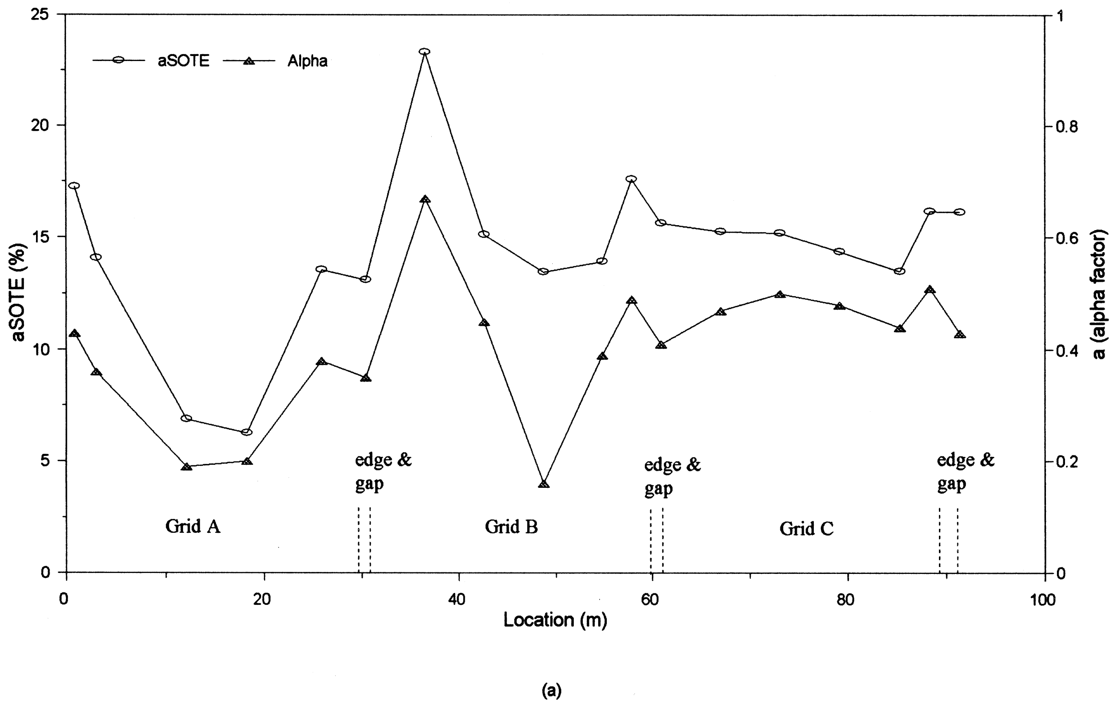


Fig. 9. Time series offgas data for Grids A and B (fixed hood position) of Tank 15 at TWRP, 02/18/98 and 02/19/98 (8:00 am–3.00 pm): Grid A (a) efficiency and alpha factor, (b) air flux and dissolved oxygen; Grid B (a) efficiency and alpha factor, (b) air flux and dissolved oxygen.

Analysis

The most direct comparison between the results from 1997–1998 and the earlier ones is provided by comparing the 1991–1993 results with the "grid interior" columns of Table 2. For example, they show that the efficiencies determined in this way for Tanks 15 and 16 in October 1997 are only slightly higher than those in July 1993, but are well below those observed in 1991 and 1992. On the other hand, the averages computed by including the gaps and edges are only slightly higher than those for the



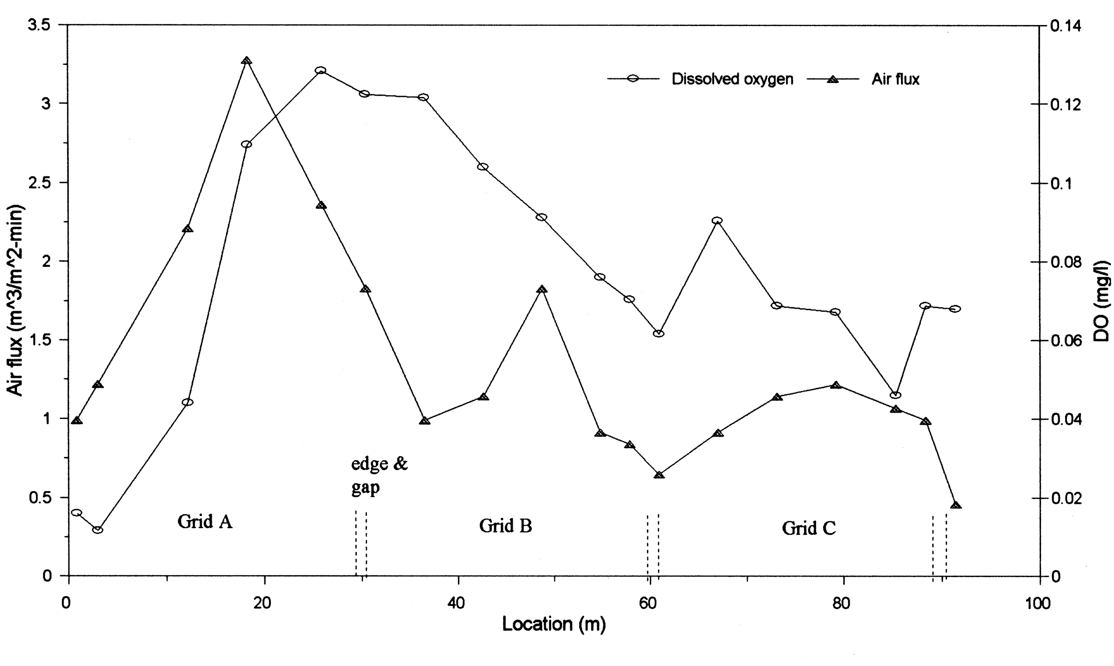


Fig. 10. Offgas data for Grids A, B and C (interiors, gaps and edges) of Tank 15 at TWRP, 03/04/98 (9:00 am–3.00 pm): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature.

grid interiors, verifying that samples in the grid interiors have provided good estimates of mean tank efficiency.

The uncertainties in Table 2 are the flow- and area-weighted standard deviations of the means in that Table, which were estimated from the samples that are shown in the figures. Although these samples were undoubtedly subject to some fluctuation, as suggested by the fixed-position measurements in Fig. 9, the experimental methods used in the fall of 1997 did not allow assigning uncertainty estimates to the individual samples. An attempt will be made in future measurements to make several measurements in quick succession at each station to assess short-term variability.

The measurements at fixed hood positions late in February on Tank 15 (Fig. 9, Table 2b), produced results consistent with the conventional scan over the tank performed on 4 March (Fig. 10, Table 2a). The results from Grid A of Tank 15 were recorded at about 15 m (50 feet) from the influent end, and observations at nearby positions on 4 March 1998, shown in Fig. 10 also produced very low OTE estimates. Likewise, the higher efficiencies in Grid B agree well with the observations at the same position on 4 March. Moreover, the March 1998 data (shown in Fig. 10), agree fairly well with the October 1997 data for Tank 15 (shown in Fig. 4), allowing for a little additional fouling in the more than 4 months between mid-October and early March.

On the other hand, significant temporal variation was observed in the fixed hood position measurements in Fig. 9. This occurred on short time scales, and the control room data show that it was probably not associated with diurnal variations in flow and biological load on the tank. The data from fixed hood positions in Tank 16, Table 2b, are also generally compatible with the previous scan on 22 October in Fig. 5.

DISCUSSION AND CONCLUSIONS

Discussion

Left-right asymmetry and longitudinal sampling. Transversal sampling is convenient for making averages across each partition to get longitudinal profiles of measured parameters, but it takes an entire working day to progress from one end of a tank to the other, so that a portion of the resulting profile is almost certainly the result of diurnal fluc-

Table 2. Oxygen transfer efficiencies of tanks in phase II of TWRP: (a) Phase II operation: multiple hood positions, (b) Phase II operations: fixed food position

Date	Tank no.	Efficiencies of Grids (A + B + C) (average ± standard deviation)			
		Grid interiors		Overall (grid interiors, gaps and edges	
		OTE	αSOTE	OTE	αSOTE
(a)					
04/05/91	15	15.20 ± 0.95	16.70 ± 1.06	not available	
04/05/91	16	15.30 ± 1.94	17.10 ± 2.43	not available	
07/01/92	15	12.70 ± 1.25	15.10 ± 2.59	not available	
07/01/92	16	13.00 ± 2.95	15.90 ± 4.13	not available	
07/22/93	15	9.60 ± 2.22	10.20 ± 2.68	not available	
07/22/93	16	10.80 ± 1.76	11.80 ± 2.21	not available	
10/16/97	15	10.35 ± 2.56	12.74 ± 2.74	11.04 ± 2.86	13.74 ± 3.35
10/22/97	16	10.20 ± 1.28	12.36 ± 1.35	11.03 ± 2.21	13.24 ± 2.40
10/23/97	14	9.08 ± 1.47	11.25 ± 1.57	9.18 ± 1.40	11.43 ± 1.55
11/05/97	14R + L[a]	10.07 ± 1.98	12.59 ± 2.55	10.12 ± 1.93	12.69 ± 2.52
11/05/97	14R[a]	10.88 ± 2.26	13.68 ± 2.56	10.92 ± 2.08	13.83 ± 2.41
11/05/97	14L[a]	9.48 ± 1.50	11.69 ± 2.31	9.45 ± 1.48	11.69 ± 2.28
02/10/98	11	13.09 ± 1.94	16.56 ± 2.38	13.36 ± 2.06	16.99 ± 2.69
03/04/98	15	9.22 ± 3.24	11.72 ± 3.84	9.72 ± 3.42	12.46 ± 4.30

Date	Location	Efficiencies (average ± standard deviation)	
		OTE	αSOTE
(b)			
Tank No. 15			
02/18/98	Grid A; center	4.10 ± 1.91	4.73 ± 2.26
02/19/98	Grid B; center	12.25 ± 1.25	15.51 ± 1.68
02/25/98	Grid C; center	12.36 ± 1.14	15.90 ± 1.63
Tank No. 16			
03/03/98	Grid A; leading left edge	6.95 ± 1.40	7.07 ± 1.46
03/11/98	Grid B; right, center	14.57 ± 0.96	18.50 ± 1.94
03/12/98	Grid C; trailing left edge	11.90 ± 1.71	13.55 ± 2.05

tuations instead of representing permanent tank conditions.

Since less time was spent maneuvering the hood with ropes stretched across the tank when longitudinal sampling was done on 5 November 1997, it was possible to get from the influent to the effluent end of the tank much sooner, so that the profiles along each side were less likely to be affected by diurnal variations. However, some measurements from opposite sides at the nearby longitudinal positions were separated by several hours, so that diurnal variations may contribute to observed differences, especially near the influent end, where the lag between the left and right measurements was greatest.

This appears to be the explanation why the efficiency results on the right side of Tank 14 are systematically higher than the results on the left side, although they show similar variations within and between the grids. The right-side data were recorded in the morning, when the air flow was between 1100 and 1200 scfm (approximately 35 and 40 standard m^3/min) most of the time, except for a decrease to below 600 scfm (approximately 20 standard m^3/min) for most of the time between 10:10 and 11:40 am. This latter period covered the last few right-side measurements and the first few left-side measurements, all of which were made at the downstream edge of Grid C. After that, the majority of the left-side measurements were made when the flow was around 1400 scfm (48 standard m^3/min). These results are consistent with the expected anticorrelated between air flow and efficiency.

Fixed hood positions. Some of the variability observed in the fixed hood measurements may be the result of hydrodynamic effects. One reason why OTEs in the field are less than those in the laboratory is of course that the bubble stream from a diffuser tends to entrain the water through which it is rising, so that the entrained water becomes more nearly saturated and little oxygen is transferred to the rest of the water. Huibregtse *et al.* (1983) note that for a grid of diffusers one would expect a cellular circulation pattern to be set up by this entrainment, but at a depth of 4.6 m, which is very close to the depth of the TWRP basins, they sometimes observed a spiral pattern. It therefore appears possible that temporal variations in the circulation, resulting from the interaction between the bubble entrainment process and the longitudinal flow in the tank, may partly explain the observed fluctuations.

The variations observed in these sessions indicate that previously expected diurnal variability is not the only source of uncertainty in the individual measurements of OTE. Thus, the averaged OTEs are subject to some additional uncertainty beyond that inferred from the variations in individual measurements incorporated into the averages. This additional uncertainty increases the threshold for inferring that differences in estimates of tank average efficiencies are sufficiently significant to justify action to clean or repair an aeration system.

Efficiency peaks. One possible reason for higher efficiencies around the boundaries of the grids, is differential fouling of the diffusers. Observations in Tanks 6 and 7 while they were dewatered confirm reports of operator experience that diffusers in the middles of the lateral pipes tend to be more fouled than those near the main manifold or near the ends of laterals. Hence, a portion of the enhanced oxygen deficiency could be attributed to this phenomenon.

Another possible explanation is available for the high efficiencies derived from the measurements made at the influent end, before the beginning of Grid A. As noted in the Experimental Setup section, aeration is performed in the distribution channel to keep solids from settling on their way from primary treatment. A small fraction of this air is likely to be entrained, and brought into the influent end of the tank, from which it would bubble to the surface. Any air that had been trapped in this way for an unusually long time with the influent would be expected to have more oxygen depletion than air that had bubbled freely from the bottom of the tank to the top.

Oxygen uptake and the α variations. Usually the most important parameter in converting OTE to αSOTE is the DO at the point of the sample, since the transfer rate is highly sensitive to the concentration gradient from the bubble to the water. For example, in Table 2 the αSOTE values are always larger than the corresponding OTE values, because they are computed from local values that are adjusted to what they would have been if DO had been zero. However, when the DO concentration is less than 0.5 mg/l, as it often is near the influent ends of tanks, the adjustment is small, so the differences between the αSOTE and the OTE values in Table 2 primarily reflect the adjustments made toward the effluent ends.

As the oxygen storage capacity of the water is small compared to the typical local bacterial oxygen uptake rate (OUR), local DO depends primarily on the balance between OUR and the local oxygen transfer rate, and hence diffuser performance. OUR, in turn, depends on the biological load posed by the combination of primary effluent and return activated sludge that formed the mixed liquor being observed, and also on the previous aeration history of the water as it has moved in approximate plug flow from the influent end to the point of observation (Suescun *et al.*, 1998; Iranpour *et al.*, 2000b).

In looking for a physical or chemical explanation of the observed α values, it is significant that the fluctuations of α closely follow the fluctuations of αSOTE in the data from each of the measurement sessions. Mathematically, this is inevitable, since

αSOTE is the product of α and SOTE: SOTE varies only modestly, because it depends only on the variations in air flux, but αSOTE displays large fluctuations, implying large changes in α. However, this conclusion makes it necessary for any proposed mechanism to explain why α can vary rapidly with position or time.

Surfactants in wastewater have long been suspected of a primary role in determining α (Masutani and Stenstrom, 1991). This is an attractive hypothesis, because it is intuitively plausible that surfactant molecules collected on the surface of a bubble would interfere with oxygen transfer through the surface. However, Hwang and Stenstrom (1985) compared surfactant concentration to bacterial OUR for their relative importances as influences on α, and found the counterintuitive result that, at least under the conditions of their experiments, OUR was statistically more important, being anticorrelated with α.

It is reasonable to ask whether this matters, since the overall purpose of the Masutani and Stenstrom paper was to argue for replacing α with dynamic surface tension (DST) as a more physically meaningful parameter. However, Hwang and Stenstrom's result is not merely about α, but is an observation of an additional influence on K_La, the volumetric mass transfer coefficient that Masutani and Stenstrom wished to determine from DST. Hence, Hwang and Stenstrom's anticorrelation is potentially relevant in a wider context than the simple mass transfer theory within which α was originally introduced. Nevertheless, as α is still widely used elsewhere, it was calculated above, and provides a useful basis for the discussion in this paper.

Newbry's (1998) exposition of a gas transfer theory can be adapted to provide a plausible explanation for both the Hwang and Stenstrom result and our observations. Newbry's equations assume clean water, not saturated with oxygen, with no CO_2, and with nitrogen and argon in equilibrium with the air, so that oxygen diffusion into the water is the only net gas transfer considered. However, the equations are derived in sufficient detail that one can see easily from them that a significant transfer of CO_2 or any other inert gas from water to a bubble would result in a faster decrease of the partial pressure of oxygen in the bubble as it rises (Iranpour *et al.*, 1999a, b).

Since the partial pressure is the driving force for oxygen transfer, a more rapid decrease of partial pressure during an unchanged rise time reduces the total oxygen transfer. From this viewpoint, Hwang and Stenstrom's anticorrelation of OUR and α is understood to have resulted from the positive correlation of CO_2 production with OUR, so that an increase in consumption of oxygen caused an increase in production of CO_2 that was transferred into the bubbles. This interpretation is consistent with the large-scale variations of α and DO in our results, which both rise along the tanks. Since DO rises despite the tapered aeration, this indicates a relatively rapid overall decrease in OUR. We hope soon to test this CO_2 transfer hypothesis with an instrument that measures CO_2 concentrations.

It is possible that to some degree the observed small-scale variations in α may also result from variations in local OUR during the tests, but local variations in fouling appear to be a more plausible explanation. The diffusers produce a distribution of bubbles of different sizes, so fouling can easily shift the distribution toward bubbles of larger sizes, even if the total flow through the diffuser is little changed. Since the surface/volume ratio of larger bubbles is smaller, less oxygen is transferred, and α decreases.

Cleaning and repair. We hope to examine economic aspects of offgas monitoring of tank efficiency in more detail in a future publication. However, since the ultimate purpose of this work is to provide improved information for decisions on aeration system maintenance and repair, a few remarks may be appropriate here.

The economic analysis of whether to clean the diffusers would involve not only assessing the efficiency improvements of cleaning the diffusers themselves, but also the value of repairs that would be possible if the tanks were dewatered for cleaning: replacement of broken diffusers and blown gaskets, and tightening of loose pipes. The 1989 study by Stenstrom and Masutani found that such damage was quite widespread in a tank at the Whittier Narrows Plant, although there was no way to know about it during normal operation. In a recent paper (Iranpour *et al.*, 1998, 2000a) we have examined evidence for development of such damage over a few weeks, as shown in OTE measurements at TWRP in Phase I during the early months of 1998. This study shows the potential value of more comprehensive offgas measurements for finding such damage without the cost and inconvenience of dewatering.

Responses to detection of rapid losses of aeration system efficiency also may deal with harm to the diffusers caused by cessations of aeration, resulting either from intentional shutoffs or from power failures, which in recent years have occurred at the TWRP about once a month. It takes only a few minutes for water leaks to fill the air distribution pipes, as shown by the large amounts of water that come out of the air release valves when aeration resumes. This causes some degree of air-side fouling of the diffusers, which is not affected by external cleaning processes. Also, during a power failure the loss of air pressure allows the external water pressure to drive suspended solids and bacterial slime that has grown on the diffusers into their surfaces, causing much more rapid fouling than normal operation.

A major barrier to enhanced OTE monitoring has been the lack of availability of equipment and expertise for performing these measurements. At present the authors are one of only three known groups performing regular OTE measurements. However, it now appears likely that a measurement system usable by plant operators can be developed by combining laptop or other portable computer technology with more convenient instruments, for which the devices used in 1997 and 1998 may be considered to be prototypes. As the research program has progressed, the operators and management at the Los Angeles plants have become strongly interested in regular monitoring of the OTE in their tanks, and it is anticipated that the operators will soon be observing OTE for themselves. This will greatly decrease the cost of these measurements.

CONCLUSIONS

A program of OTE measurements at TWRP has been successful in meeting its dual objectives of measuring the average standardized process water efficiencies in several tanks and exploring the consequences of innovations in sampling patterns. A new sampling pattern has been tried that separates the results from the left and right sides of a tank and allows faster coverage of a whole tank. Measurements with fixed hood positions provide insight into temporal variability.

Results from several tanks show similar patterns, including enhanced efficiencies at the upstream and downstream edges of the aeration grids and in measurements over the gaps between grids, which have not been observed before on these tanks. These variations are believed to result primarily from differences in diffuser fouling along the lateral pipes, such as has been observed in dewatered tanks, with a possible contribution at the influent end from air entrained from the aerated distribution channel.

Sufficiently detailed OTE measurements offer the prospect of providing much more specific information about the nature and location of damage than what could be obtained by any other method short of dewatering the tanks and directly inspecting the pipes and diffusers. Results from the present study suggest that achieving this level of detail is likely in most cases to involve observing offgas from significantly more of a tank's surface than the 2% recommended by the EPA for determining overall tank efficiency.

It is likely that more remains to be learned about the tanks at TWRP that will be of local interest. However, the present results are evidence of the potential value of more thorough monitoring of oxygen transfer in aeration basins than what has been common practice in the past and provide a possible starting point for similar work elsewhere.

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