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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. © 2000 Elsevier Science Ltd. All rights reserved

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, aSOTE, which provides the most uniform basis for comparing aeration efficiencies observed at different times and places. Then the a parameter measures the reduction in OTE caused by wastes. a is defined by the equation $a = aSOTE/SOTE$, 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 aSOTE 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.

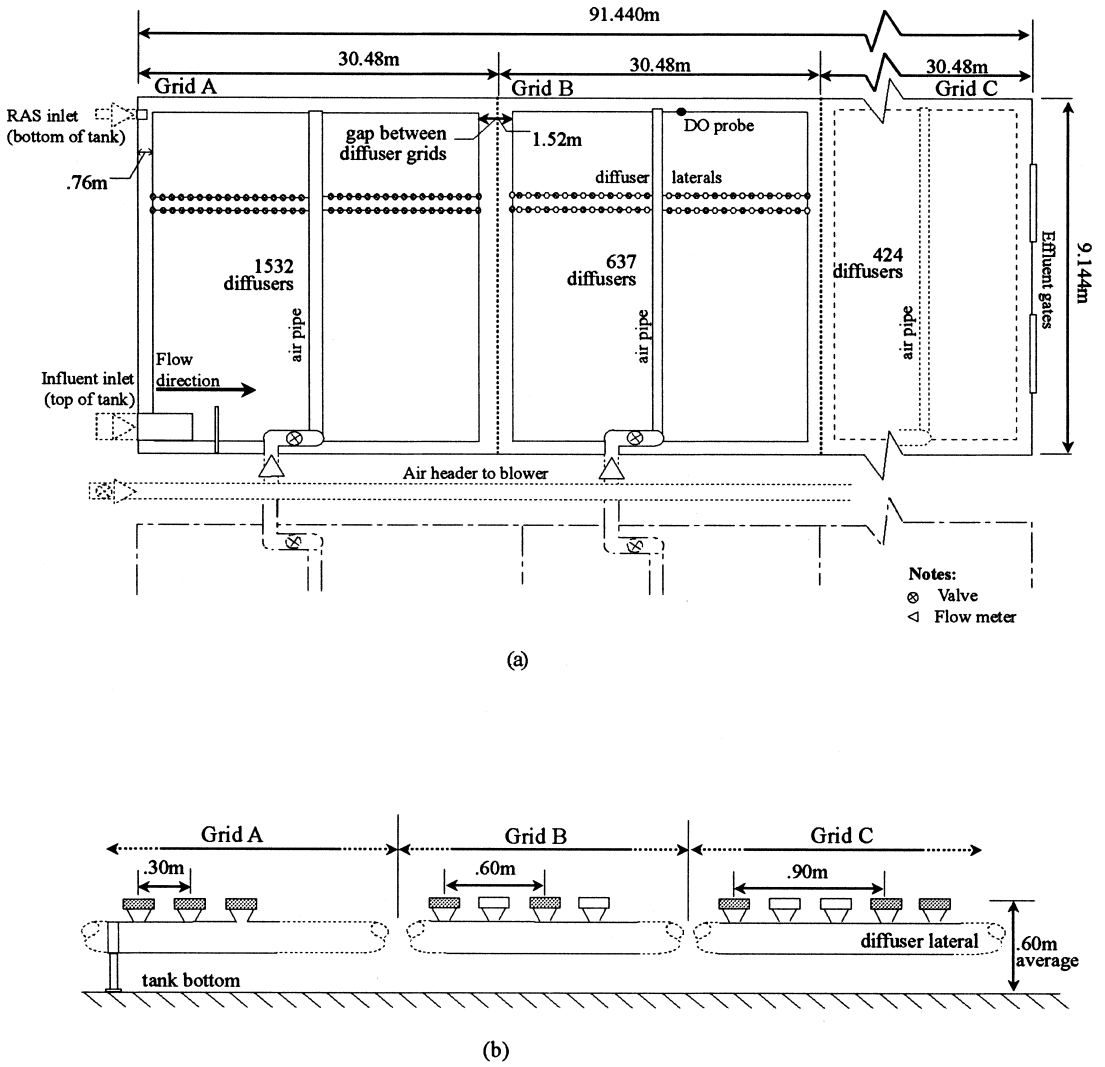

Fig. 1. Plan views of a tank structure in phase II of TWRP: (a) dimensions and components of aeration tanks, (b) dimensions of diffusers in tanks.

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 $1 \ddot{y} r^{0}$. 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

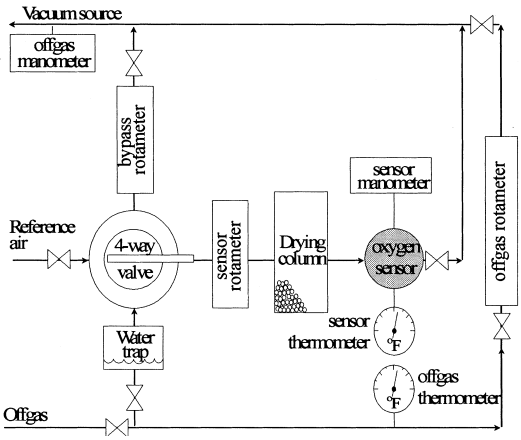

Fig. 2. Plan views of Ewing of OTE analyzer structure.

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:

$$\overline{OTE} = \frac{\sum_{i=1}^{n} A_i Q_i OTE_i}{\sum_{i=1}^{n} A_i Q_i}$$

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, $\overline{OTE}$ 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 aSOTE. 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 aSOTE according to the following formula:

$$aSOTE = \frac{OTE \; C_{\alpha 20}}{(\Omega b C_{\alpha T} - DO)\gamma^{T-20}},$$

where $C_{\alpha 20}$ is the equilibrium DO concentration at 20°C, 760 mm barometric pressure, zero salinity, $C_{\alpha T}$ is the equilibrium DO concentration at temperature T, 760 mm barometric pressure, zero salinity, Ω is the barometric pressure correction factor, b is the salinity correction factor, $= C_{\alpha}$ process water/C_{α} clean water, γ 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 a is computed by dividing aSOTE, determined from the formula above, by SOTE, according to the equation $a = aSOTE/SOTE$. 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 a.

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

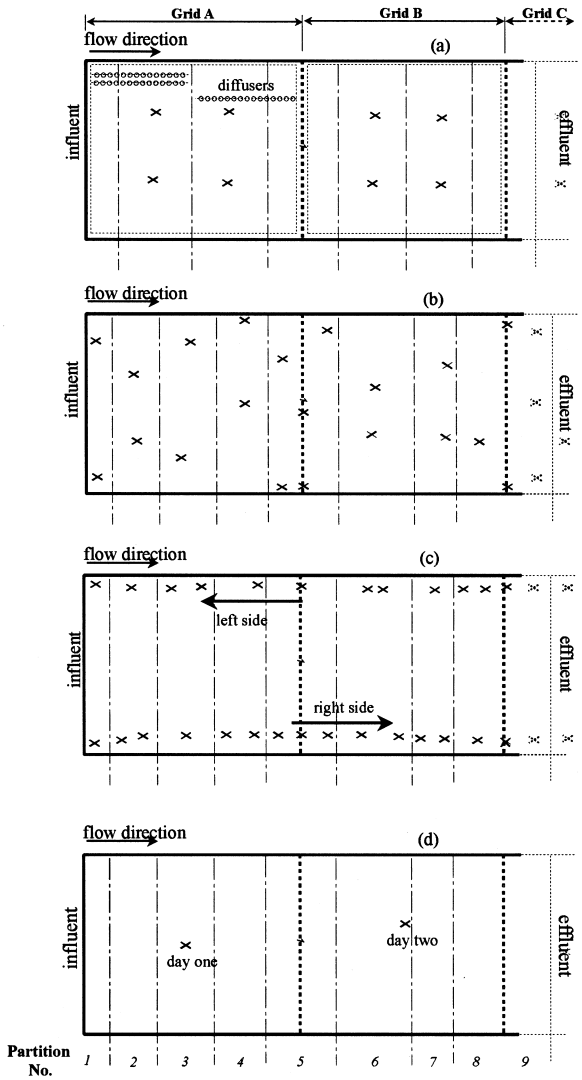

Fig. 3. Sampling layouts applied to different tanks at TWRP: (a) transverse sampling (1991–1994), (b) transverse sampling (1997–1998), (c) longitudinal sampling (1997–1998), (d) stationary sampling (1997–1998).

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.

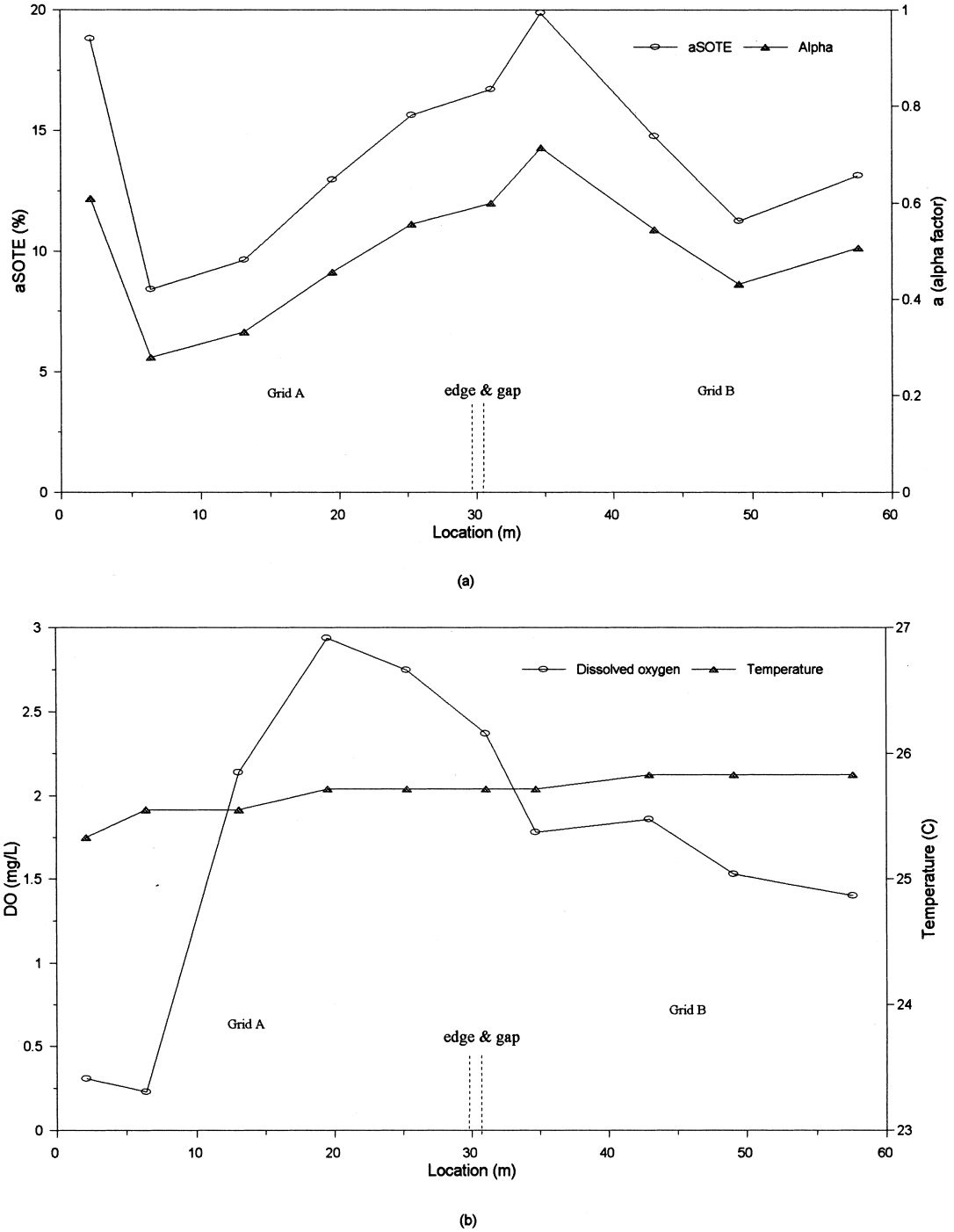

Fig. 4. Offgas data for Grids A and B (interiors, gaps, and edges) of Tank 15 at TWRP, 10/16/97 (9:00 am–1.30 pm): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature.

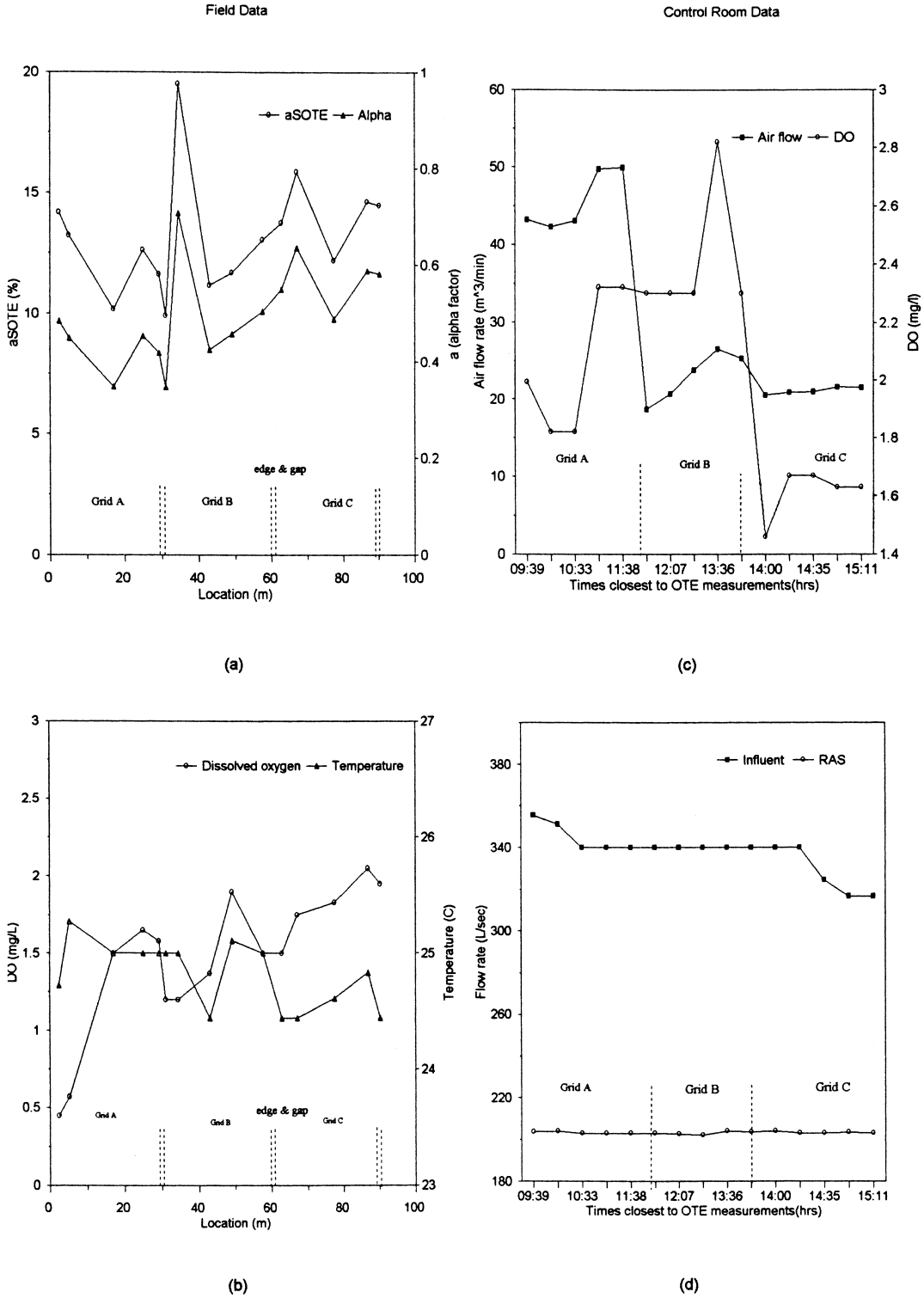

Fig. 5. Offgas data for Grids A, B and C (interiors, gaps, and edges) and Control Room data of Tank 16 at TWRP, 10/22/97 (9:00 am–3.30 pm): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature, (c) air flow rate and dissolved oxygen as a function of time, (d) flow rate and RAS as a function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

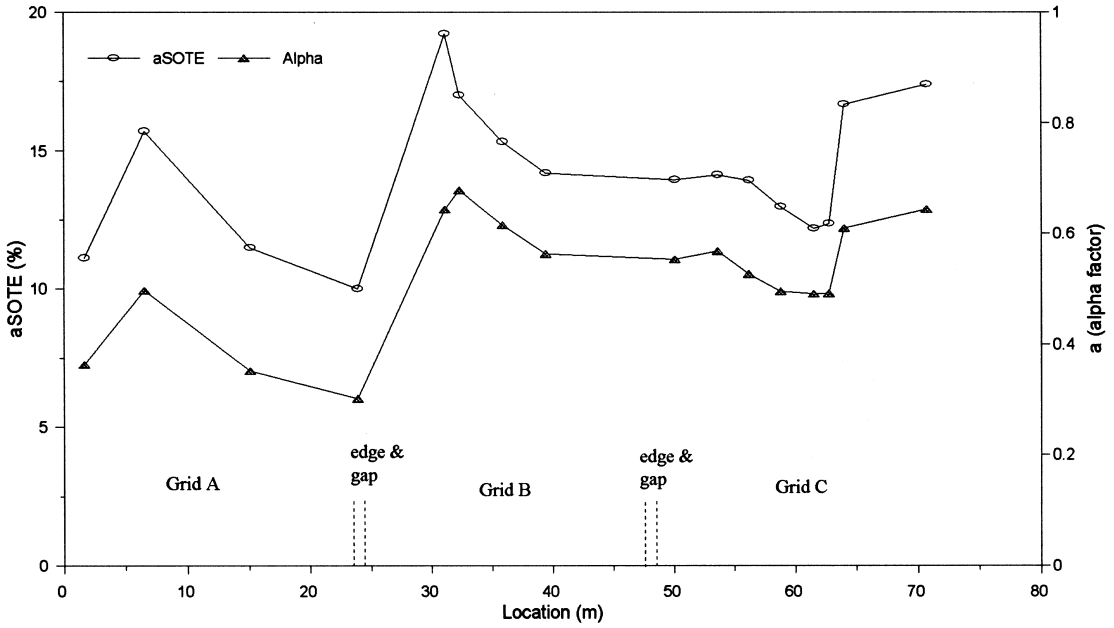

Fig. 6. Offgas data for Grids A, B and C (right side edges and gaps) of Tank 14 at TWRP, modified sampling pattern, 11/05/97 (9:00 am–11.00 am): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature.

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.

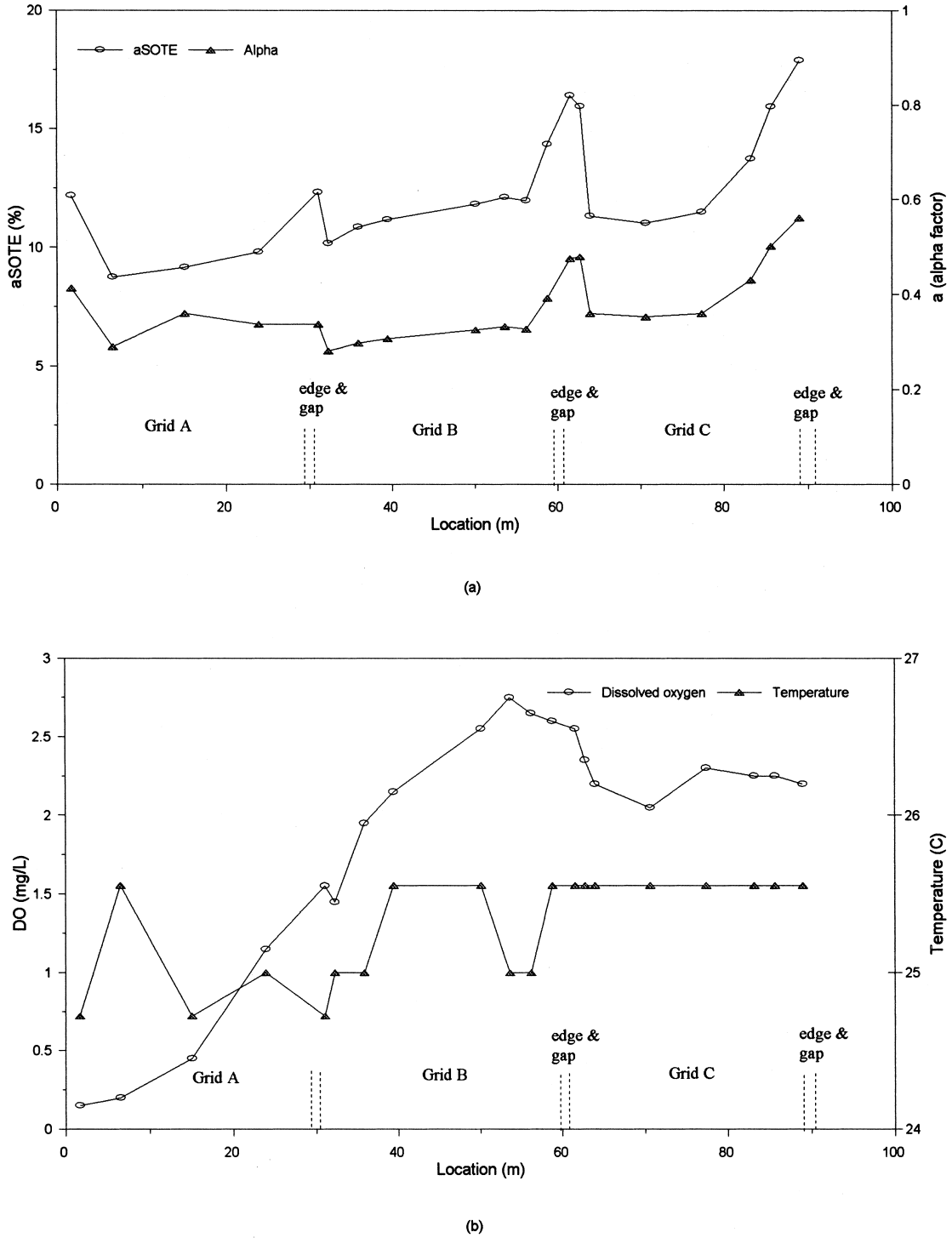

Fig. 7. Offgas data for Grids A, B and C (left side edges and gaps) of Tank 14 at TWRP, modified sampling pattern, 11/05/97 (11:00 am–1.30 pm): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature.

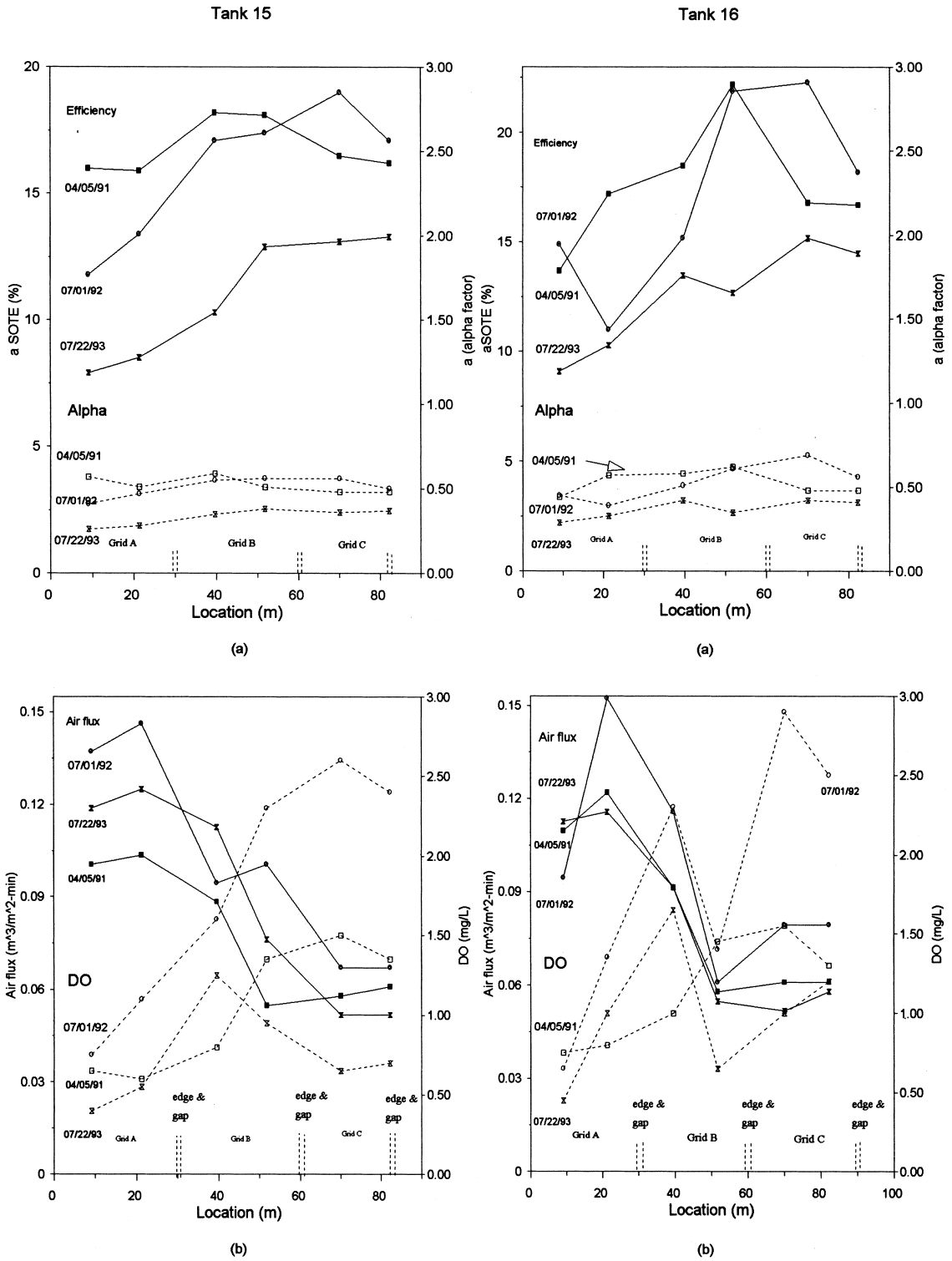

Fig. 8. Offgas data for Grids A, B and C (interior only) of Tank 15 and Tank 16 at TWRP, 04/05/91, 07/01/92 and 07/22/93 (8:00 am–3.30 pm): Tank 15 (a) efficiency and alpha factor, (b) air flux and dissolved oxygen; Tank 16 (a) efficiency and alpha factor, (b) air flux and dissolved oxygen.

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.

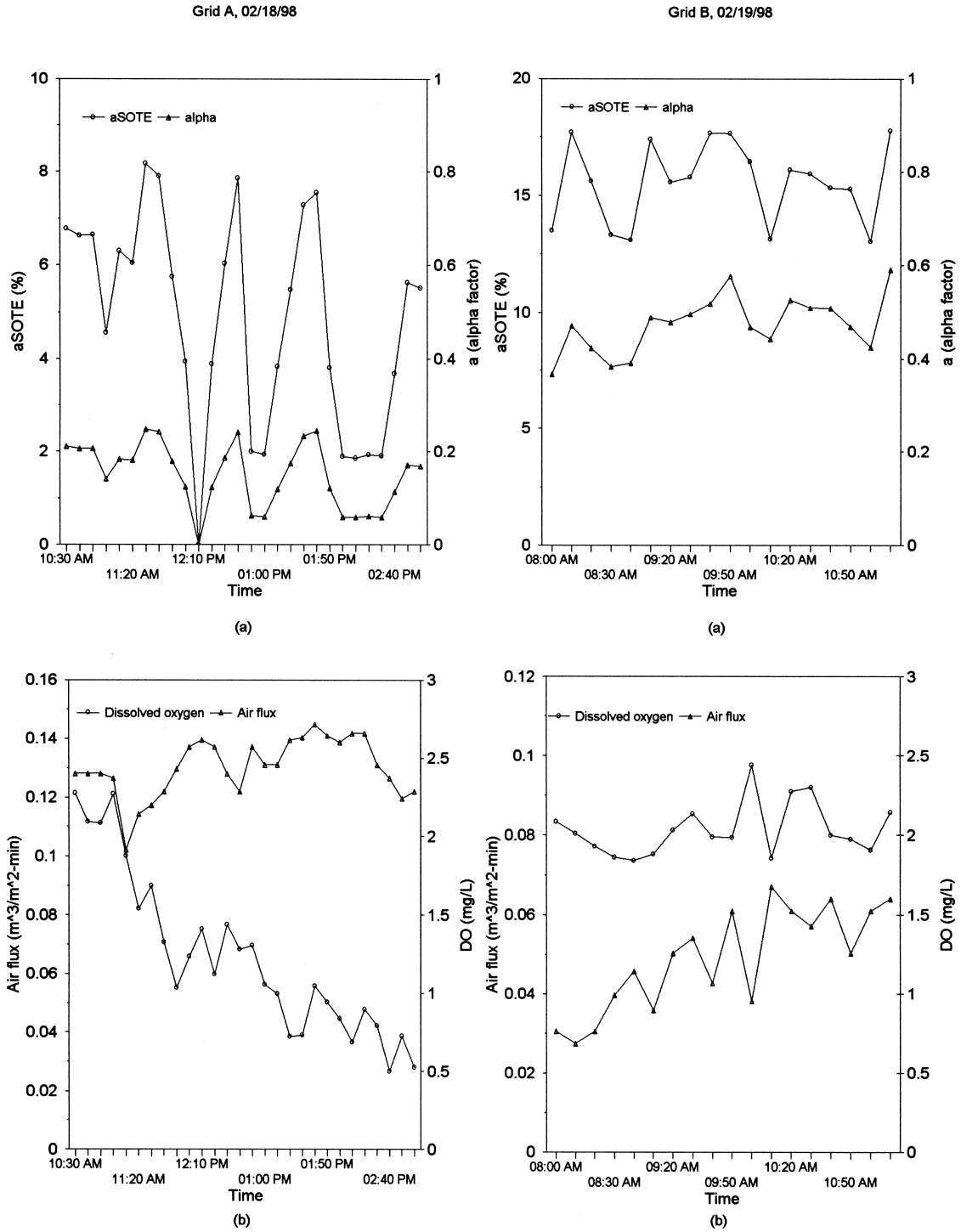

Fig. 9. Time series offgas data for Grids A and B (fixed hood position) of Tank 15 at TWRP, 02/18/98 and 02/19/98 (8:00 am–3.00 pm): Grid A (a) efficiency and alpha factor, (b) air flux and dissolved oxygen; Grid B (a) efficiency and alpha factor, (b) air flux and dissolved oxygen.

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

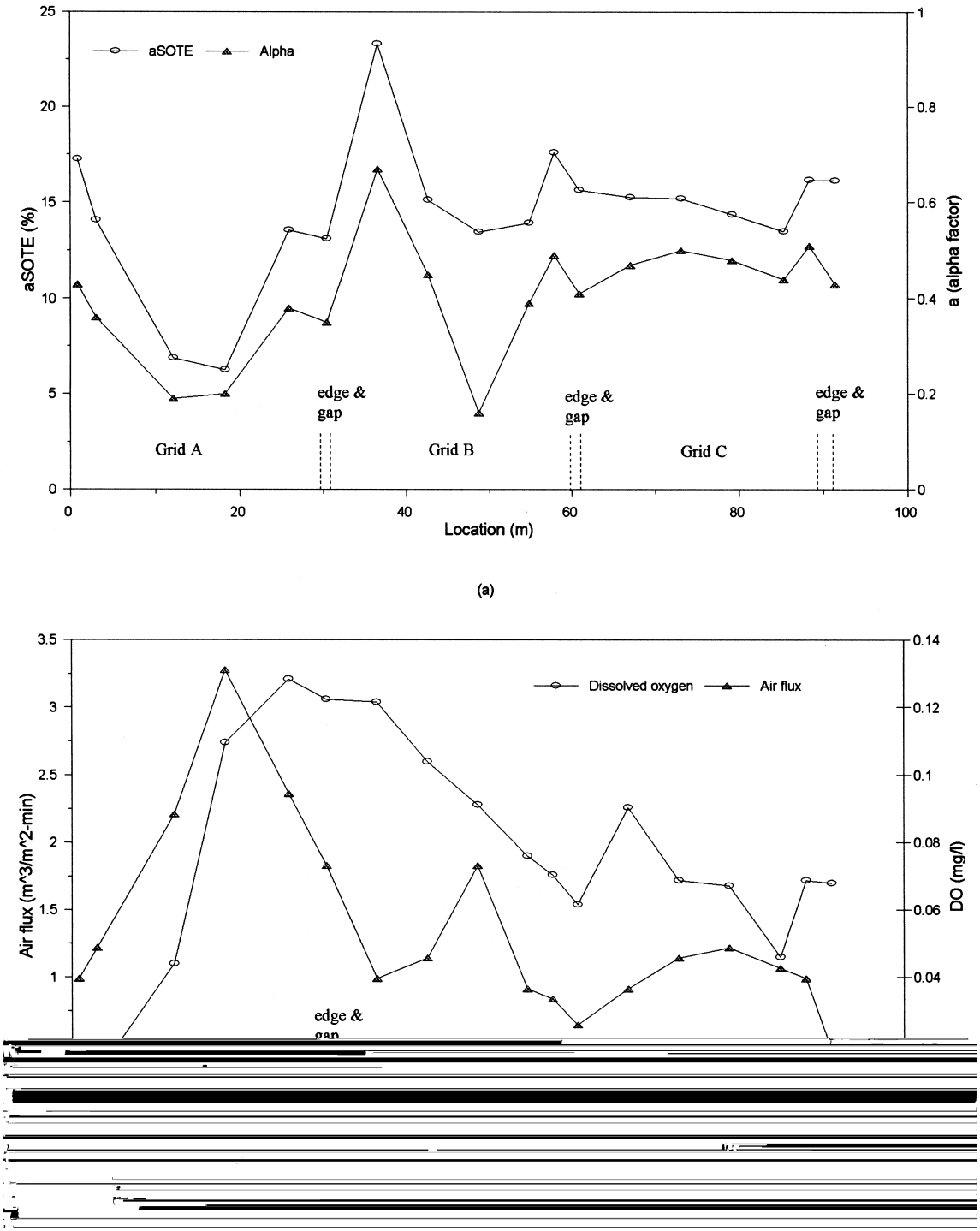

Fig. 10. Offgas data for Grids A, B and C (interiors, gaps and edges) of Tank 15 at TWRP, 03/04/98 (9:00 am–3.00 pm): (a) efficiency and alpha factor, (b) dissolved oxygen and temperature.