Relationship Between Oxygen Transfer Rate and Airflow for Fine-Pore Aeration Under Process Conditions

Reza Iranpour, Michael K. Stenstrom

ABSTRACT: Although feedback systems that control the air supply to aeration tanks inherently incorporate some assumption about oxygen transfer response to changes in airflow, it is rare to measure this relationship under process conditions. This paper reports measurements of oxygen mass-transfer curves (MTCs) for a tank at the Tillman Water Reclamation Plant in Los Angeles, California. The curves were obtained by measuring the oxygen transfer efficiency (OTE) at selected points for several set values of airflow while the plant was operating. They approximate inverted parabolas because increasing the airflow increases the amount of oxygen supplied by the blowers, but decreases the OTE, which is the fraction of the supplied oxygen that actually enters the water. Data were recorded from both recently cleaned diffusers and ones that were moderately to severely fouled.

The peaks in the curves from the fouled diffusers are at or below the midpoints of the observed ranges of airflows. Hence, there is only a narrow range of usable airflows between the lower limit, determined by the manufacturer of the diffusers, and the peak of the MTC, which is the maximum amount of oxygen that can be supplied. The peaks for the cleaned diffusers are higher, which allows more ability to adjust to changing biological loads.

These results show that existing dissolved oxygen control systems may not be adequate and that fouling may reduce not only the overall efficiency of an aeration system but its ability to respond to changes in the biological load. The measurements also provide some insight to the limitations of using sparsely distributed dissolved oxygen sensors to control the aeration process and the excess costs that are incurred by the consequent need to compensate for uncertainty with extra air. However, additional testing is needed to determine whether the present results are aberrant or typical of tanks with fouled or cleaned diffusers. *Water Environ. Res.,* **73,** 266 (2001).

KEYWORDS: mass-transfer curve, aeration, oxygen transfer efficiency, diffuser maintenance, sampling, optimal airflow, parameter estimation, valve opening, curve fitting.

Introduction

This paper reports new results from a program of oxygen transfer efficiency (OTE) measurements at the Los Angeles, California wastewater treatment plants. This program has been conducted as part of a multifaceted, larger program to reduce costs and improve efficiency.

This study examined the ability of the aeration system to respond to changing loads: during each measurement session, one aeration grid of a tank was taken out of the control of the plant's automated air supply, and OTE measurements were made with airflows fixed at known values by manually setting the valves. This allowed computation of the grid's oxygen mass-transfer curve (MTC), which is the mass of oxygen that actually dissolves in the water per unit time, expressed as a function of airflow.

A standardized parameter known as αSOTE (computed from raw OTE values by adjusting for nonstandard temperature, pressure, humidity, and salinity at the experimental site) was used to establish a uniform basis for OTE measurements. The MTC derived from αSOTE is designated αMTC, and this is the quantity presented in the Observation and Analysis section.

Basic physical considerations indicate that OTE tends to decrease with increasing airflow. Diffuser manufacturers often provide standardized OTEs as functions of airflow in clean water, but it is less common to make such measurements under operating conditions. The only other MTC results presently known to the authors are collected in the report of Allbaugh et al. (1985). This lack of data is understandable because such measurements are time-consuming and laborious, especially using the instruments for offgas measurements of OTE that have been available until recently. Also, adjusting tank airflows for the conditions of a particular measurement session is likely to be inconvenient for operators and may possibly cause a violation of discharge standards.

Hence, aeration control is typically conducted now with little knowledge of the actual overall change in OTE caused by an airflow change. The limitations of this approach become clear after considering that it is not always true that larger airflows transfer more oxygen. That is

$$O_2 \text{ mass-transfer rate} = \text{OTE} \times O_2 \text{ mass flow in the air}$$

so at great enough airflows a further flow increase may decrease oxygen transfer because the reduction in OTE may more than offset the effect of additional oxygen availability in the greater flow. Thus, the MTC approximates an inverted parabola, with one region that has a positive slope and another with a negative slope.

In practice, if airflow increases to the point that the MTC has a negative slope, then two things happen: (a) control procedures that assume a positive slope produce results opposite to those expected and (b) energy is wasted in providing a large flow of air that transfers no more oxygen than a smaller flow at the corresponding point on the positive slope of the MTC. Typically, it would not be expected that the airflow in a tank would be so high that oxygen transfer starts to decrease for the tank as a whole, but nonuniform fouling leading to this condition in the most fouled areas would not seem unusual. Confirming either case requires controlled OTE measurements on operating tanks to compute the actual MTCs.

Initial work in this area dates to Redmon and Boyle (1981), Redmon et al. (1983), Campbell (1982), and Ewing (1993) who developed modern offgas testing. Stenstrom and Masutani (1989) and Iranpour et al. (1997a, 1997b, 1998a, 1998b, 1999a, 1999b, 2000a, 2000b, 2000c, and 2000d) provided perspective on plant operations in Southern California. Babcock and Stenstrom's (1993) analysis of the effect of errors in the measurement process has improved confidence in the quality of results that can be obtained. The Stenstrom et al. (1984) and Currie and Stenstrom (1994) discussions of replacing ceramic diffusers with membrane devices provide a basis for analyzing the potential economic significance of this work. For a thorough analysis for design purposes, U.S. Environmental Protection Agency (1989) and ASCE (1993) are the essential references. Significant references for current information on aeration are Fisher and Boyle (1999), Newbry (1998), Semmens et al. (1999), and Iranpour et al. (1999a and 2001).

The goals of this study are: to optimize air use and thereby to reduce costs, to assess the effect of diffuser fouling on the ability of the aeration system to respond to changing loads, and to demonstrate the value of making this kind of measurement. The specific objectives are: to obtain standardized OTE measurements at several points in one or more grids, to compute the equivalent mass-transfer values at these points and the aggregate values over the grids, and to obtain curves from the data to estimate the maximum useful airflow in each grid.

Experimental Setup

The study was carried out in aeration tank 15 at the Tillman Water Reclamation Plant (TWRP), which is located in the San Fernando Valley, California, with an average flow of approximately 2600 L/s. The tank is a rectangular reactor, 9 m wide, 90 m long, and 4.6 m deep, equipped with Aercor (Brown Deer, Wisconsin) ceramic dome diffusers 2.30 mm in diameter (Figure 1). In June 1999, the diffusers received their first cleaning since 1996, so the measurements in April and August 1999 allowed assessment of the effect of cleaning. An independent valve and DO sensor installed for each grid makes it possible to establish a fixed airflow for one grid that does not affect the operation of the rest of the tank.

Grid A, the grid at the influent end, was chosen for the first set of measurements in the hope that if the study included setting the aeration there to insufficient levels, the aeration levels of subsequent grids could be adjusted to compensate. Also, tank 15 is only one of approximately 12 aeration tanks in operation at the plant at any time, so that variations in treatment effectiveness in this one tank would be diluted among the effluent of the rest of the tanks, and there would be little risk of violating the plant discharge standards.

The measurements in grid A were made at the four locations shown in Figure 1. Four locations were also used in grid B. These locations were chosen to provide the most uniform sampling that could be achieved with a relatively short measurement time that would allow repetition at all locations at each of several airflow settings within 1 working day.

Experimental Procedure

Overall OTE measurements were conducted on tank 15 on October 16, 1997, and on March 4, 1998. Mass-transfer curve measurements were made in grid A on April 13 and 14, 1999, and in grid B on April 19, 1999. Additional measurements were conducted in grid A on August 7 and 8, 1999, more than 1 month after the diffusers were cleaned in June. As in the April sessions, the August 7 and 8 sessions were limited to approximately 6 hours a day at the request of the operators, to minimize the risk of disturbing tank operation with the airflow adjustments. Also, a more systematic variation of airflow from low to high was used in August.

The same procedure was followed at each valve setting on each day. The team adjusted the valve and recorded its position and the airflow indicated by the control room. During the following period of approximately 1 hour, the research team then measured the OTEs, first at the upstream locations, 7.6 m from the influent end (A and B, Figure 1), and then at the downstream locations, 24 m from the influent end (C and D, Figure 1). This was repeated for four or five valve settings.

Only a relatively narrow range of the possible valve openings was used. This was dictated by equipment limitations 17 to 43%. Use of the manufacturer's minimum recommended airflow of 0.014 2 standard m^3/min per diffuser (which for the approximately 1500 diffusers in grid A gives approximately 21.2 m^3/min as the minimum flow to the grid) corresponded to a valve opening of approximately 17%. Because of a loss of balance in various gauges on the OTE instrument, the readings did not stabilize for valve openings greater than 43%.

The measurement crew recorded the temperature and the dissolved oxygen (DO) at the location of the collection hood, and the offgas instrument had a fuel cell that measured the O_2 partial pressure after removal of CO_2 and water vapor from the sample stream. The formulas for the conversion to the standardized parameter typically denoted as αSOTE and the averaging with respect to both area and airflow are given in Redmon et al. (1983) and Iranpour et al. (2000c).

Every few minutes, the control room equipment also automatically recorded data from the plant's built-in field instruments. For the times closest to the times of the off gas measurements, the researchers tabulated four parameters for the grids from these data: process water and return activated-sludge flow into the tank, airflow to the grid, and DO from the grid's sensor.

The αMTCs in this paper are calculated from the αSOTE values. This not only makes them more comparable to each other on successive days, but also allows comparison with the standardized results reported by Allbaugh et al. (1985). Because DO is the largest contributor to the standardization factor, the differences between the raw OTEs and the αSOTEs are small at low DO values, which are typical at the influent end of a tank, such as in grid A.

Observations and Analysis

Grid Averages for Moderate to Severe Fouling. Figure 2 shows the efficiencies and the mass transferred into the water as functions of the airflow, averaged over grid A on April 13, 1999. The airflows are extrapolated from the local airflow measurements made during the OTE measurements. It is possible that they may be influenced by local fouling, which would explain why they sometimes differ by approximately 20% from the airflows to the whole grid recorded from the control room data.

As shown, the largest valve openings used were sufficient to reduce the efficiency well below 1%, so that there would have been little value in making measurements at openings greater than approximately 40%, even if the offgas instrument had allowed this. The OTE data show substantial scatter, instead of forming the expected smooth downward-sloping straight or nearly straight line, so this scatter carried over to the mass-transfer values. Nevertheless, the primary conclusion from Figure 2 is that over most of the observed range of airflows, at each of the four measurement locations, mass transfer decreased with increasing airflow. Only in

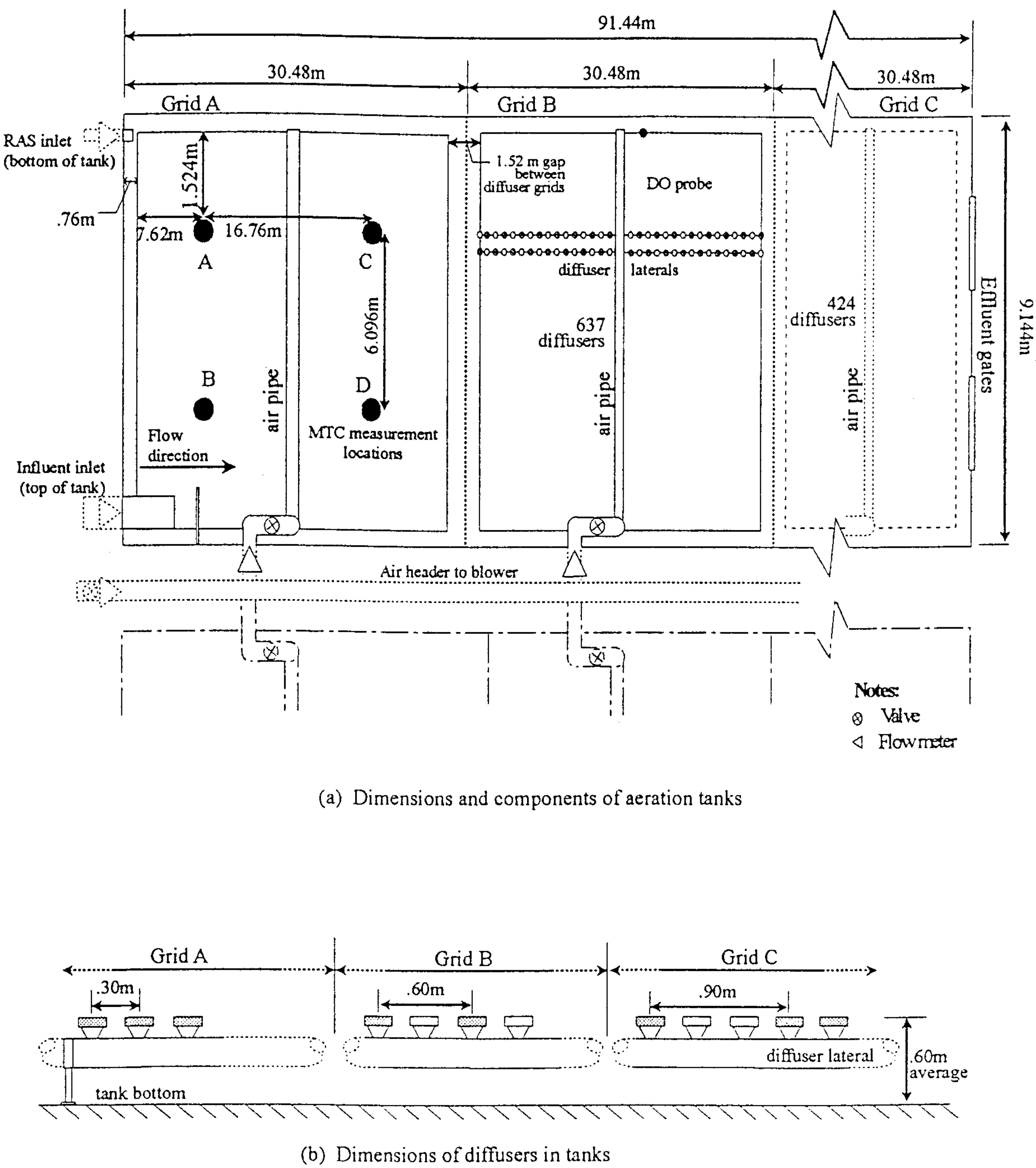

Figure 1—Plan view of an aeration tank and MTC measurement in grid A.

the lower half of the range of airflows did mass transfer increase or remain steady with increasing airflow.

Figure 3 shows the corresponding values for the April 14, 1999, session. Most of the valve settings used on this day differed only slightly from those used on April 13, and comparing Figure 3 with Figure 2 shows that similar valve settings typically, but not always, produced similar results. The raw data (not shown) provide additional details of this variation in the degree of agreement, including the fact that the DO concentrations measured for the αSOTE correction are systematically lower on April 14 than on April 13, suggesting a greater biological load. On April 13, the DO values at 7.6 m from the influent end were approximately 0.5 mg/L and at 24 m they were approximately 2.5 mg/L. However, on April 14, all DO values were less than 1.1 mg/L, and at 7.6 m they were all less than 0.6 mg/L. Additional measurements would be required to determine whether the largest differences between the αSOTEs for corresponding positions and similar flows on the two days are real or measurement mistakes.

Making all allowances for the uncertainties implied by the scatter in these data, and the differences from the April 13 measurements, it is clear from Figure 3 that, as on April 13, the OTEs decrease so rapidly, and reach such low levels, that the mass-transfer values decrease with increasing airflow over most of the interval observed.

Figure 4 presents aggregate data for grid A from both days,

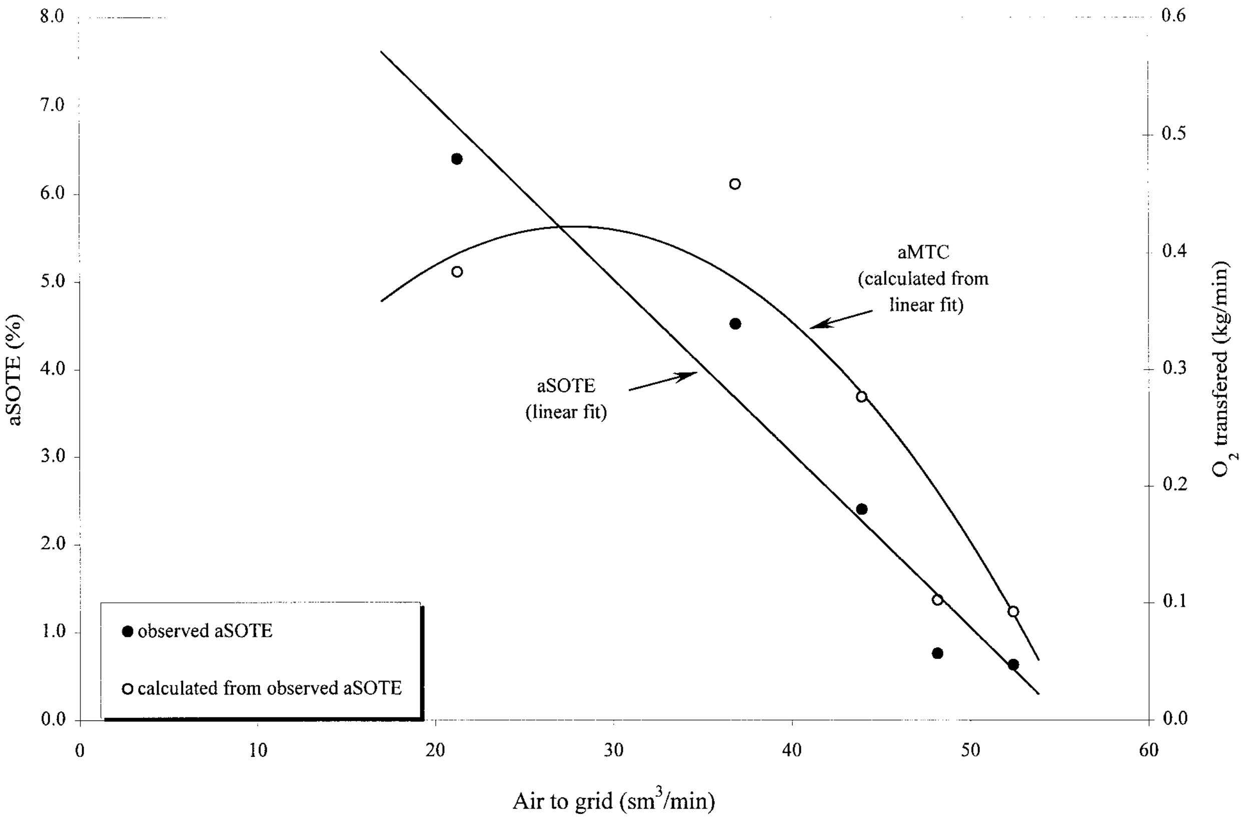

Figure 2—Efficiency and MTC for grid A, tank 15, TWRP, April 13, 1999.

where each point is obtained by averaging over the four locations at one of the airflow settings. As would be expected from the plots for the individual days in Figures 2 and 3, the plot in Figure 4 shows steady or increasing mass transfer between 21.2 and approximately 28.3 standard m^3/min, and decreasing mass transfer at greater flows. This is clear despite the previously noted moderate differences between the April 13 and 14 data, which can be easily seen when they are combined on one plot.

Figure 5 shows the results from the April 19, 1999, measurements on grid B. They were taken over a narrower range of valve settings (25 to 40%) than the grid A measurements, and the fit indicates that the mass transfer was steady or declining over this interval.

Averages by Location. Figure 6 combines the April 13 and 14 data for each location in grid A and shows the parabolas derived from the linear fits to the OTE data. Each of these parabolas peaks at approximately 28.3 standard m^3/min. The slight differences in the peak positions for the locations do not seem to be significant because of the large scatter in the original data points.

On the other hand, it may be more significant that the mass-transfer values from the upstream side of the grid, 7.6 m from the influent end (A and B, Figure 1), are lower than those from the downstream side, 24 m from the influent end (C and D, Figure 1). This is consistent with past measurements from many researchers (Fisher and Boyle, 1999, and Iranpour et al., 1997a, 1997b, 1998a, 1998b, 1999a, 1999b, 2000a, 2000b, 2000c, and 2000d) showing that OTEs rise as treatment progresses. Because Fisher and Boyle's results seemed contrary to their expectations about the effects of selectors and surfactants, this rise of OTEs may be related to the declining bacterial oxygen uptake rate (OUR) as treatment progresses, as suggested by the results of Hwang and Stenstrom (1985). Results of this study are strongly consistent with a relatively rapid decline of OUR along the length of the tank because the DO measurements in the raw data at 24 m from the influent end were typically greater than 1 mg/L, but at 7.6 m they were almost always less than 1 mg/L. However, these results do not provide enough detail to assess how much of this difference is the result of a difference in OUR and how much results from the more rapid fouling that is typically observed at influent ends, where the high substrate concentrations, and perhaps the low DO concentrations, are especially favorable for biofilm growth on the diffusers.

Recently Cleaned Diffusers. Figure 7 shows the combined results from the August 7 and 8, 1999, sessions with cleaner diffusers. As expected, the OTEs are much greater than these indicated in Figure 4, although the DO concentrations were not much different from the April data (less than 1.0 mg/L at 7.6 m from the influent end and 1.0 to 2.0 mg/L at 24 m). The peak of the MTC occurs at a much greater flow than in April. On the other hand, the slope of the line fitted to the OTE data is steeper than the lines fitted to the earlier data, presumably reflecting changed bubble formation fluid dynamics after cleaning.

Estimating Maximum Allowable Airflow. Because the airflow at the peak of the MTC is the maximum of the usable range of airflows, the maximum allowable airflow was estimated as summarized here. For an αSOTE dependence that is well fitted with a straight line, as used in the data above, there are two significant parameters: the constant term c_0 and the coefficient of the linear term c_1, where $c_1 < 0$, so that the estimating function is αSOTE = $c_0 + c_1 q$ for an airflow q, from which is derived αMTC $\sim c_0 q + c_1 q^2$. Thus, the peak airflow q_p is

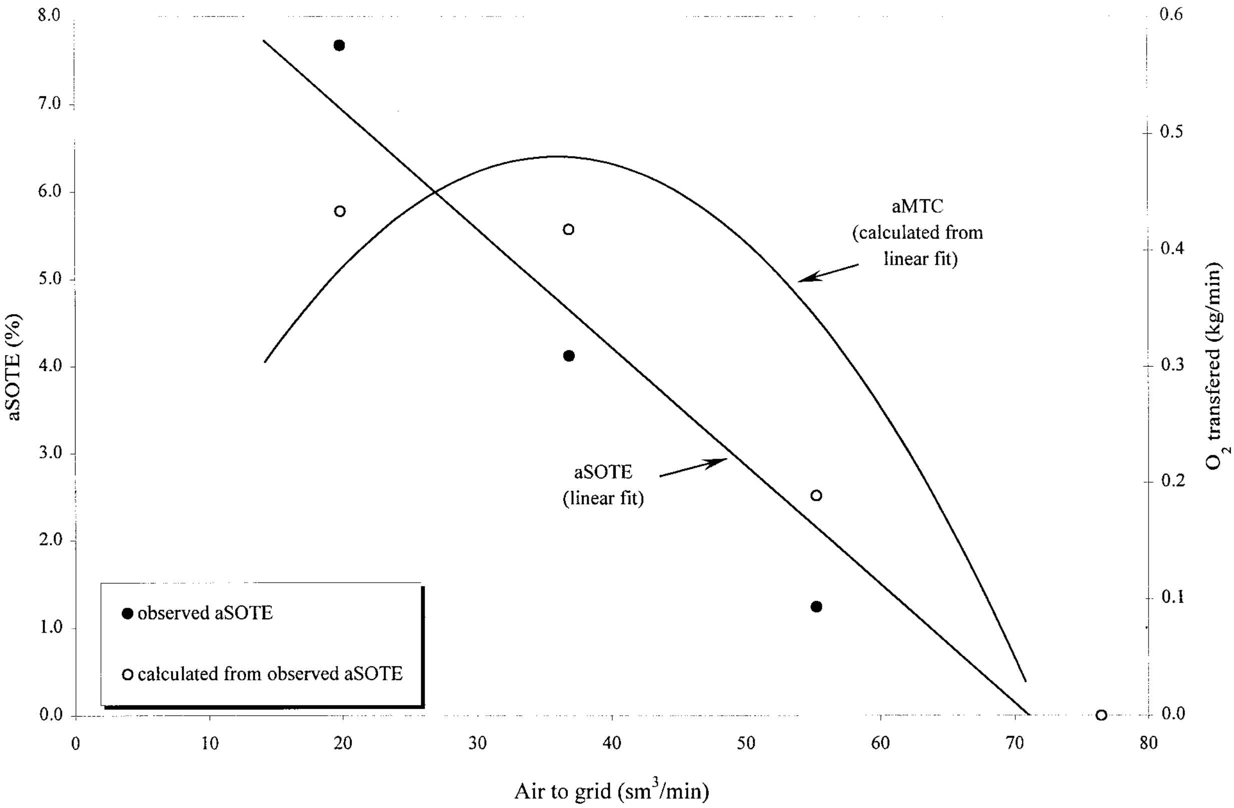

Figure 3—Efficiency and MTC for grid A, tank 15, TWRP, April 14, 1999.

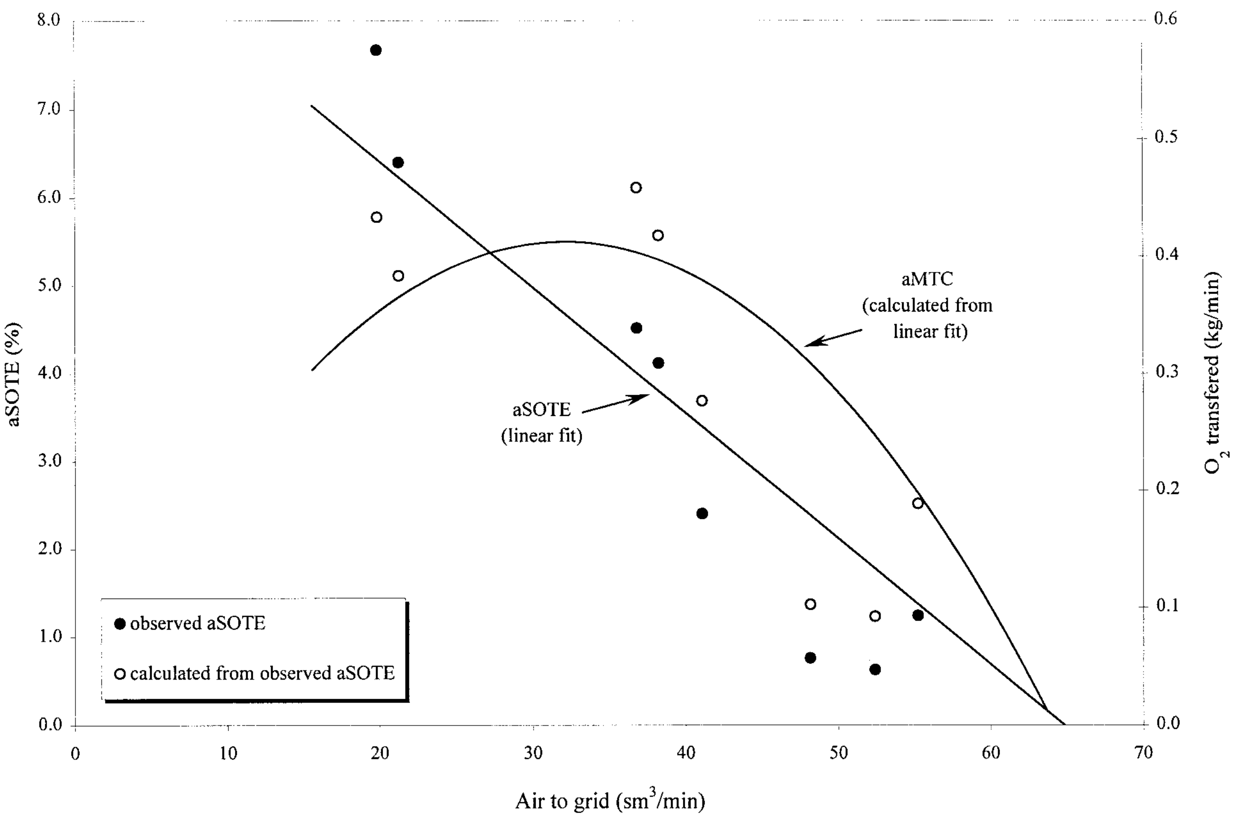

Figure 4—Efficiency and MTC for grid A, tank 15, TWRP, April 13 and 14, 1999.

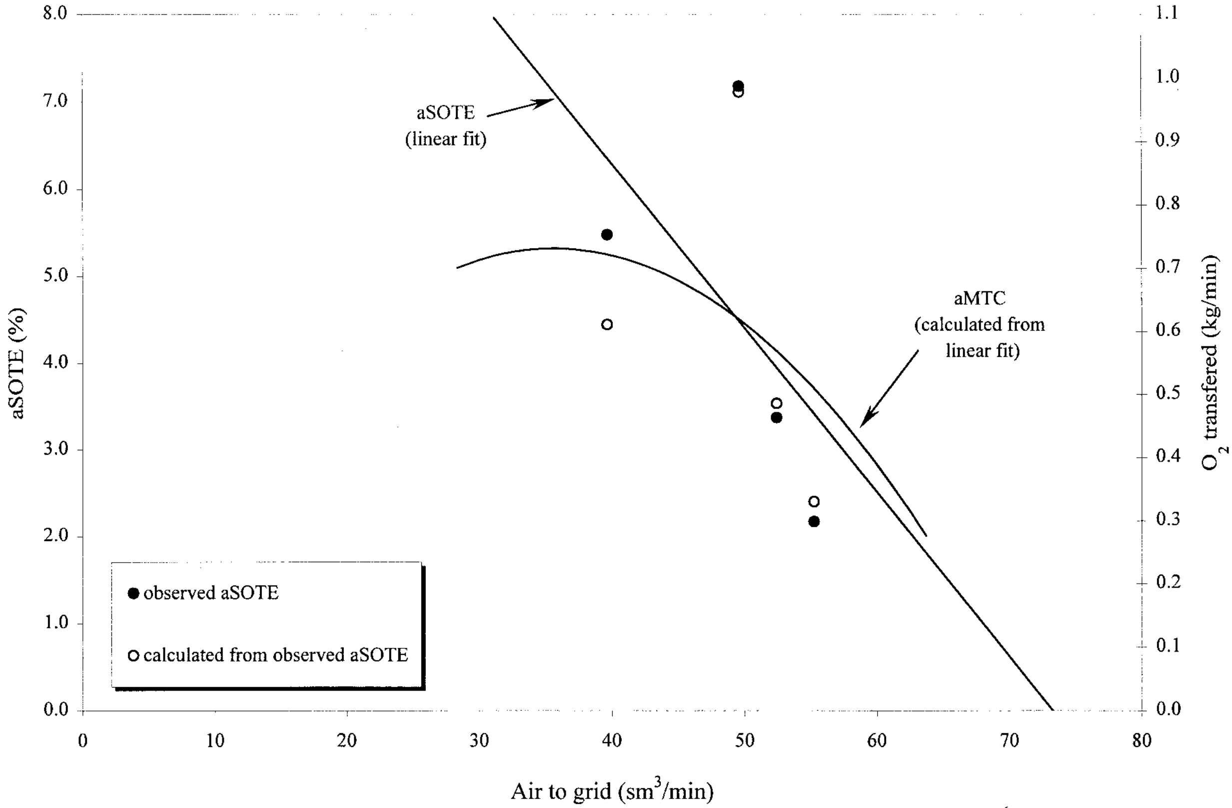

Figure 5—Efficiency and MTC for grid B, tank 15, TWRP, April 19, 1999.

$$q_p = -c_0/2c_1 \qquad (1)$$

Changing c_1 to a less negative slope would broaden the parabola and increase q_p, whereas increasing c_0 would shift the whole parabola to the right and also increase q_p. A schematic example of these effects is shown in Figure 8.

It is also evident that the scatter in the points would translate into uncertainty in the shape of the parabola. If c_0 and c_1 were determined by conventional least-squares fitting methods, then this uncertainty would be expressed by the estimated standard errors δ_0 and δ_1 of c_0 and c_1, which would propagate into a standard error estimate δ_q for q_p according to the formula

$$(\delta_0/c_0)^2 + (\delta_1/c_1)^2 = (\delta_q/q_p)^2 \qquad (2)$$

Thus, a prudent approach to using MTC data would be to operate over the interval from the minimum allowed by the manufacturer up to $q_p + \delta_q$. This is depicted schematically in Figure 8.

Table 1 shows estimated peak airflows and standard errors for the grid A measurements, derived from linear fits to the αSOTE data. The best estimate from the combined set of data of a maximum airflow in April is seen to be approximately 28.3 + 3.4 standard m^3/min for fouled diffusers, corresponding to a valve opening of approximately 25%. This would apply as long as the dependence of OTE on airflow was not significantly changed by diffuser system deterioration or maintenance. The last line of Table 1 gives a quantitative indication of the improvement made by cleaning, which is also evident visually from comparing Figure 7 with Figures 2 through 4. The estimated maximum airflow for the cleaned diffusers is approximately 37.3 + 5.0 standard m^3/min.

Discussion

Comparison to Previous Reports. An informative comparison with these new measurements is provided by the results reported in Allbaugh et al. (1985), whose example was followed in fitting linear functions to OTE data and computing parabolic MTCs. They computed MTCs not only for their own data from Lansing, Michigan, on September 22, 1983, but for results from a New York brewery not otherwise identified, and for a test performed in clean water at a depth of 6 m by the Los Angeles County Sanitation District, California. Because these tests were performed with differing numbers of diffusers, computing the fluxes in units of m^3/min per diffuser provides the best available comparison.

Because the conditions of the Los Angeles County test were different from the others, the peak in this test at the high flux of 0.099 m^3/min per diffuser probably is not directly comparable to the other two. The peak in the Lansing data occurs at 0.046 m^3/min per diffuser, and the New York brewery data peaks at 0.57 m^3/min per diffuser. Allbaugh et al. present dynamic wet pressure data and other evidence indicating that the diffusers in the Lansing test were no more than modestly fouled in September, 1983, but they do not give the diameters of the diffusers in any of the tests. On the other hand, all three of these studies observed peaks at fluxes at least twice the minima for the respective diffusers, as was the case for the TWRP diffusers after cleaning.

Because cleaning improved the efficiency so much, fouling is an obvious hypothesis to explain the poor behavior observed in April. On the other hand, the data do not rule out a contribution from bulk mixing patterns, a possibility that has been raised (U.S. EPA, 1989) to explain results in the Allbaugh et al. (1985) study.

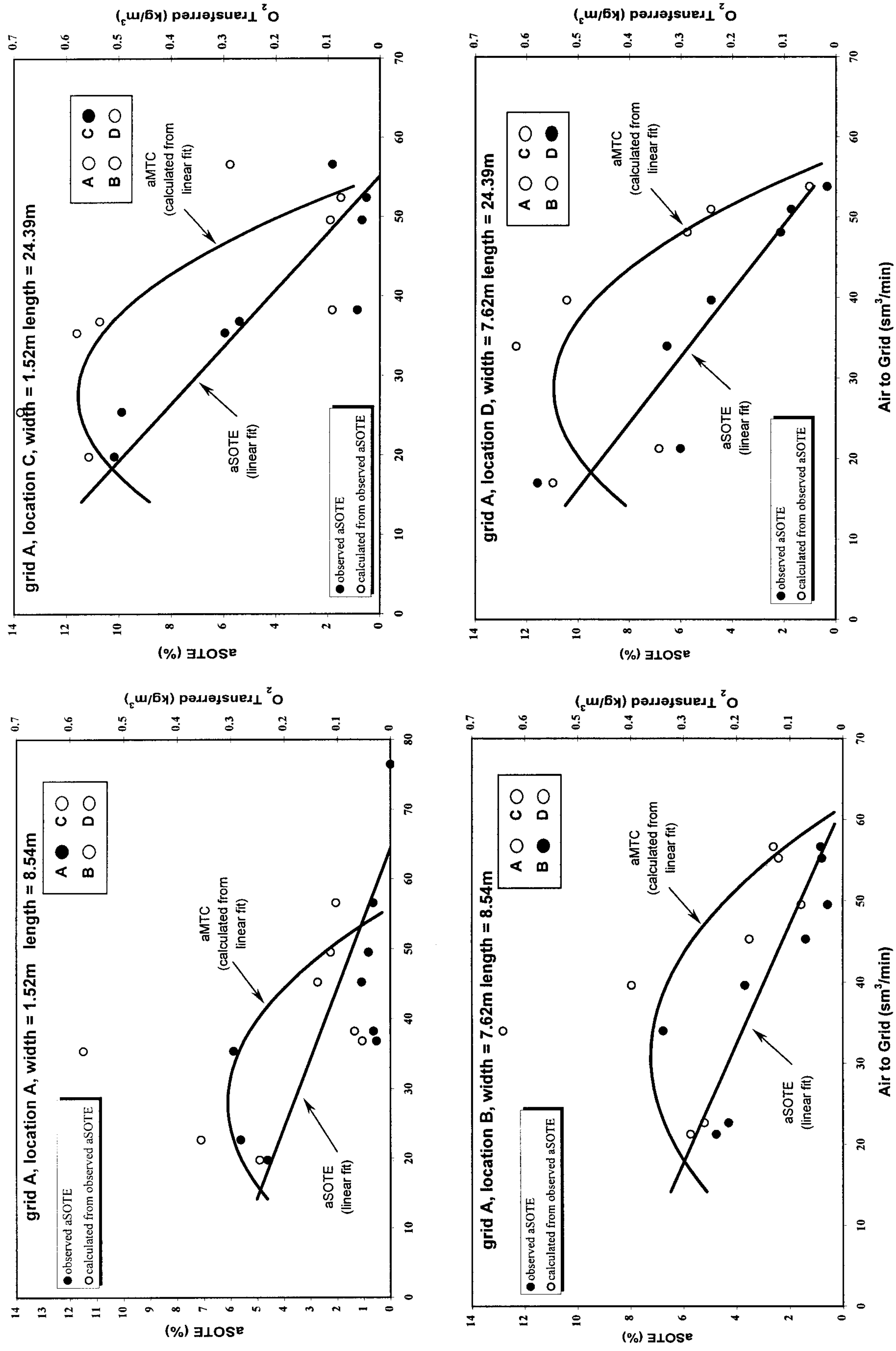

Figure 6—Efficiency and MTC at four locations for grid A, tank 15, TWRP, April 13 and 14, 1999.

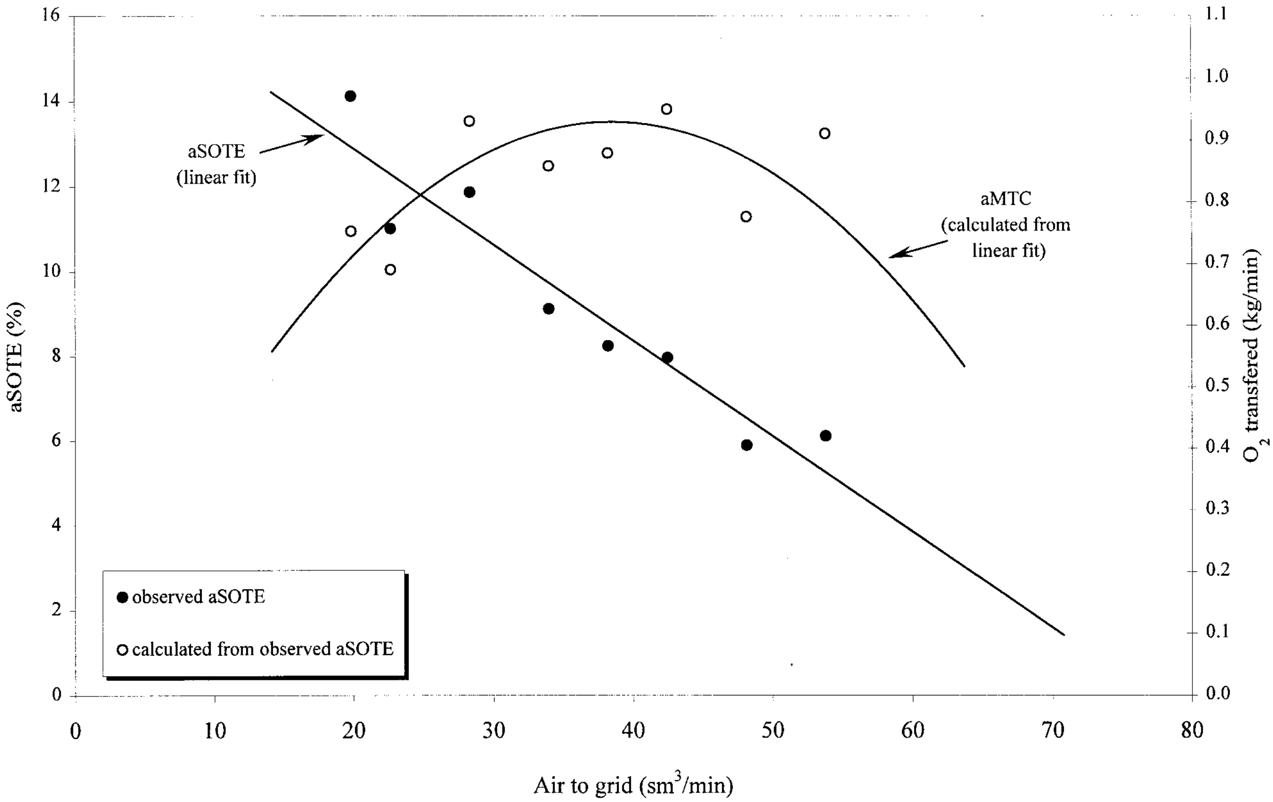

Figure 7—Efficiency and MTC for grid A, tank 15, TWRP, August 7 and 8, 1999.

These results are sufficiently striking that measurements seem desirable on other tanks at TWRP, and the other plants in Los Angeles that have similar secondary treatment systems. Further consideration suggests that if caution about affecting plant operations is the primary concern when preliminary tests are made at other plants, then using one of the downstream grids might be

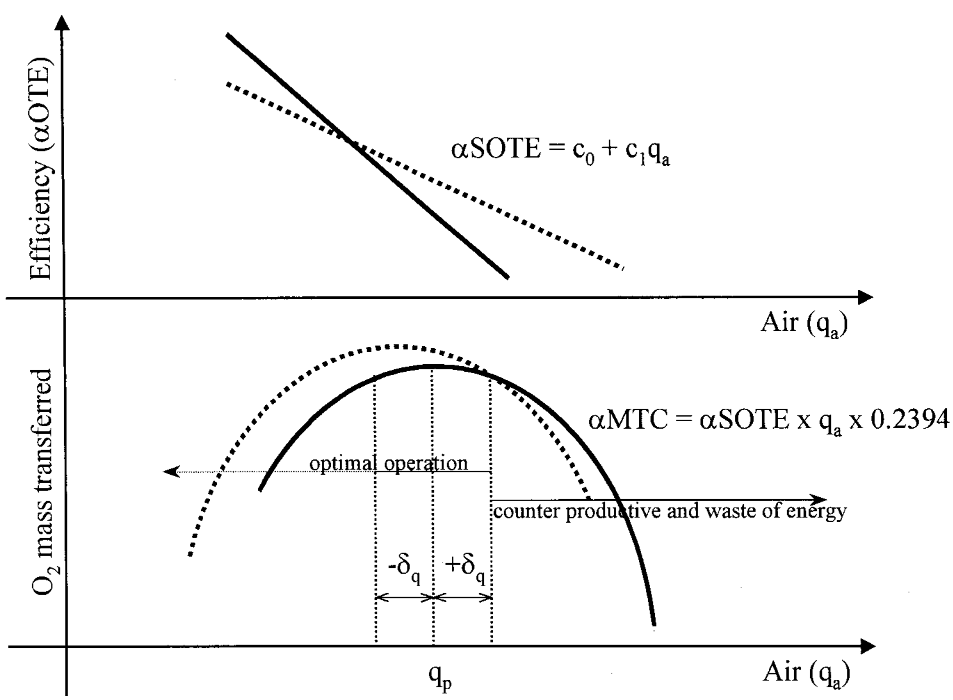

Figure 8—Schematic example of MTC and estimated maximum allowable airflow.

Table 1—Estimation of maximum air flow range for Tank 15, TWRP.

Date	Tank and grid	Condition	Air flow, q_a (sm^3/min)		
			Peak, q_p	Error, q	Peak + Error, q_{p+q}
April 13, 1999	15, grid A	Fouled	27.6	4.73	32.3
April 14, 1999	15, grid A	Fouled	35.7	8.58	44.2
April 13 and 14, 1999	15, grid A	Fouled	28.4	3.43	31.9
August 7 and 8, 1999	15, grid A	Cleaned	37.3	5.01	42.3

preferable, because so much of the tank's bacterial activity occurs near the influent end. However, the relatively brief reductions in oxygen transfer in these experiments did not cause any serious reduction in quality of the effluent from tank 15.

The Appropriateness of the Linear Approximation. It is clear that any linear function models the dependence of αSOTE on airflow only over a relatively narrow range of flows. It certainly is not physically realistic to extrapolate any straight line to flows where it predicts negative αSOTEs. (Experimental records from this study include an αSOTE that was expected to be low and was measured to be zero. However, this may be reasonably attributed to the inherent uncertainty of these measurements and the limited resolution and sensitivity of the offgas instrument, which was designed primarily for measuring larger and more practically important degrees of oxygen depletion than low levels that correspond to low αSOTEs.) A slow, asymptotic approach to the horizontal axis is the behavior expected at high airflows from simple physical considerations: ever-larger flows produce ever-larger bubbles, resulting in ever-lower αSOTEs.

This behavior is represented for SOTE by writing (U.S. EPA, 1989)

$$SOTE_a = SOTE_1(q_a)^m \tag{3}$$

Where

$SOTE_a$ and $SOTE_1$ = SOTE at airflow qa and at a flow of 0.03 m^3/min, respectively, and

m = an emperical constant for a given diffuser and system configuration (typically a fractional negative number for fine-pore diffusers).

Evidently, the same relationship would apply after conversion to αSOTE. However, the quality of the experimental data do not support highly elaborate analysis efforts. An effort to fit an equation of the form of equation 3 to the April 13 and 14 data produced an implausible exponent m equal to -2.25, and a greater mean squared fitting error than the linear model. (Because taking the logarithm of both sides of equation 3 produces a linear formula, the linear regression macro of Microsoft Excel [Seattle, Washington] was used for this test.)

Another effort to depart from linear functions was a quadratic fit, suggested by the manufacturers' clean-water SOTE formulas mentioned above. The Microsoft Excel linear regression macro was also used for this test, because it conveniently produces statistical estimates of the significance of each term. Because it estimated a 65% probability that the resulting quadratic term was actually zero, this calculation also was no better than a linear fit. Hence, the analysis in this paper uses linear fits.

Economic Perspectives. If this work were to lead to recommendations for substantial modifications and upgrades to currently installed wastewater aeration systems, then the costs of the changes would be expected to be large. However, they may be justified by the large costs of present treatment methods.

For a perspective on the magnitude of the economics involved, note the design of the tanks in the Los Angeles wastewater plants, which is typical of many large wastewater treatment plants. The power cost per tank is approximately U.S.$300/d, and there are almost always more than 20 tanks in operation. Hence, just a 10% rise in average tank OTE (such as from 10 to 11%) would reduce costs by approximately U.S.$600/d, or approximately U.S.$200 000/a. For comparison, Currie and Stenstrom (1994) report a prospective saving to the Union Sanitary District of California (located southeast of San Francisco) of approximately U.S.$140 000/a in processing 1100 L/s of wastewater, based on installing membrane diffuser systems rated at 13.8% efficiency instead of the present ceramic disks with efficiencies of 10.8%. Thus, it can be seen that modest-seeming improvements in average OTEs have the potential for significant cost savings.

In summary, improved understanding of aeration system responses to changing loads has the potential to contribute to large savings in aeration costs. This study is the most direct possible investigation of system responses.

Conclusions

Measurements of OTE conducted with fixed valve settings on both cleaned and moderately-to-severely fouled diffusers have observed αSOTE decreasing so rapidly with increasing airflow that providing more air actually decreases the amount of oxygen transferred into the process water. In such a case the system is beyond the peak of the αMTC, and control procedures that assume increasing mass transfer with increasing airflow are useless or counterproductive.

This behavior was more prevalent for fouled diffusers, for which the usable range of air fluxes was as narrow as 0.014 to 0.021 m^3/min per diffuser. This is much less than the maxima reported by Allbaugh et al. (1985) and leaves little scope for airflow adjustments to meet changing loads. Better performance was restored by cleaning. Not only was the usable range widened to 0.014 to 0.028 m^3/min per diffuser, but higher αSOTEs resulted in increased mass transfer at all airflows in comparison to the results for fouled diffusers.

The large amounts of money currently spent on secondary aeration at activated-sludge plants could justify substantial investments in improving aeration efficiency. Also, additional measurements in other tanks at this plant, and at other plants seem desirable.

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Authors. R. Iranpour is the head of the Applied Research, City of Los Angeles Bureau of Sanitation. M.K. Stenstrom is a professor at the Department of Civil and Environmental Engineering, University of California at Los Angeles. All correspondence should be addressed to M.K. Stenstrom, Department of CE and Environmental Engineering, 4173 Engr. I, UCLA, Los Angeles, CA 90095.

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