Oxygen Transfer in a Full-Depth Biological Aerated Filter

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ABSTRACT: The City of San Diego, California, evaluated the performance capabilities of biological aerated filters (BAFs) at the Point Loma Wastewater Treatment Plant. The City conducted a 1-year pilot-plant evaluation of BAF technology supplied by two BAF manufacturers. This paper reports on the first independent oxygen-transfer test of BAFs at full depth using the offgas method. The tests showed process-water oxygen-transfer efficiencies of 1.6 to 5.8%/m (0.5 to 1.8%/ft) and 3.9 to 7.9%/m (1.2 to 2.4%/ft) for the two different pilot plants, at their nominal design conditions. Mass balances using chemical oxygen demand and dissolved organic carbon corroborated the transfer rates. Rates are higher than expected from fine-pore diffusers for similar process conditions and depths and clean-water conditions for the same column and are mostly attributed to extended bubble retention time resulting from interactions with the media and biofilm. *Water Environ. Res.,* **80,** 663 (2008).

KEYWORDS: aeration, biological aerated filter, chemically enhanced primary treatment, municipal wastewater, offgas testing, oxygen transfer efficiency.

doi:10.2175/106143008X268452

Introduction

The Point Loma Wastewater Treatment Plant (PLWTP) is the largest wastewater treatment plant in the City of San Diego (California), with the capacity to produce up to 10.5 m^3/s (240 mgd) (annual average daily flow) of chemically enhanced primary treated effluent for ocean disposal. Despite fully complying with its current National Pollutant Discharge Elimination System permit, the City has elected to proactively prepare for any potential need to increase treatment efficiency, by evaluating secondary alternatives that are best suited for the land-constrained PLWTP site. Figure 1 shows the site, with schematic diagrams of the approximate footprints for the required additional facilities to upgrade to secondary treatment. The figure illustrates the space-saving attributes of the biological aerated filter (BAF) technology for this footprint-constrained site. The current plant layout is schematically shown in Figure 2. Flow passes through influent screens, grit chambers, primary clarifiers using chemical coagulation, and effluent screens. Primary sludge is conditioned in anaerobic digesters. A cogeneration gas facility recovers biogas energy as heat and electrical power. Stabilized biosolids are sent to the offsite Metropolitan Biosolids Center for final processing and disposal.

The City embarked upon the evaluation of current and new high-rate secondary wastewater treatment processes that might be compact enough to fit the existing land at the Point Loma site. The evaluation resulted in identifying the BAF process as having the most promise, given the site constraints, potential cost, performance of large-scale examples of candidate technologies, and anticipated treatment requirements. However, a lack of BAF performance data for carbonaceous removal in warm climates and the need to evaluate the BAF technology under local conditions and with San Diego wastewater motivated the City to invest in a 1-year-long pilot test. Krüger (Cary, North Carolina), supplier of the Biostyr process, and Infilco Degremont Inc. (Richmond, Virginia), supplier of the Biofor process, were identified as possessing the appropriate experience with large-scale BAF installations (>1.31 m^3/s [>30 mgd]). These manufacturers were asked to provide preliminary facility layouts and costs based on design criteria provided by the City.

Biological aerated filters are 3-phase submerged media reactors and require periodic backwashing. They are designed to use both attached and suspended biological growth. The benefits include high biological reaction rates, tolerance of high loading rates, enhanced sludge settleability, and better mass transfer between biomass and substrate (Lazarova and Manem, 1994). In BAF reactors, biochemical oxygen demand (BOD) is removed by suspended solids filtration and by metabolism of soluble organics within the biofilm (Stensel et al., 1984). Hansen et al. (2007) have compared performance of a full-scale BAF and activated sludge plant for a facility in Denmark.

Aeration studies on BAF pilot plants have been conducted in the past, with contrasting results. All observed higher oxygen-uptake rates (OURs) than generally found in the activated sludge process, which is consistent the BAF's reduced volume and hydraulic retention time. Stensel et al. (1984) measured OURs from 121 to 250 mg/L·h, in a 1.7-m-tall reactor, that were 3.0 to 3.2 times greater than the observed rates in clean water tests in the same equipment. In their investigation, Stensel et al. (1984) observed the increased OUR in a reactor where a large portion of the sparged air bubble area was in direct contact with the media. Lee and Stensel (1986) had similar findings in a laboratory-scale reactor (5 m tall × 0.05 m diameter), showing that clean-water-transfer data severely underestimate process transfer rates. In another pilot study, Canziani (1988) observed increases in k_La as high as 100% in columns (3.5 m

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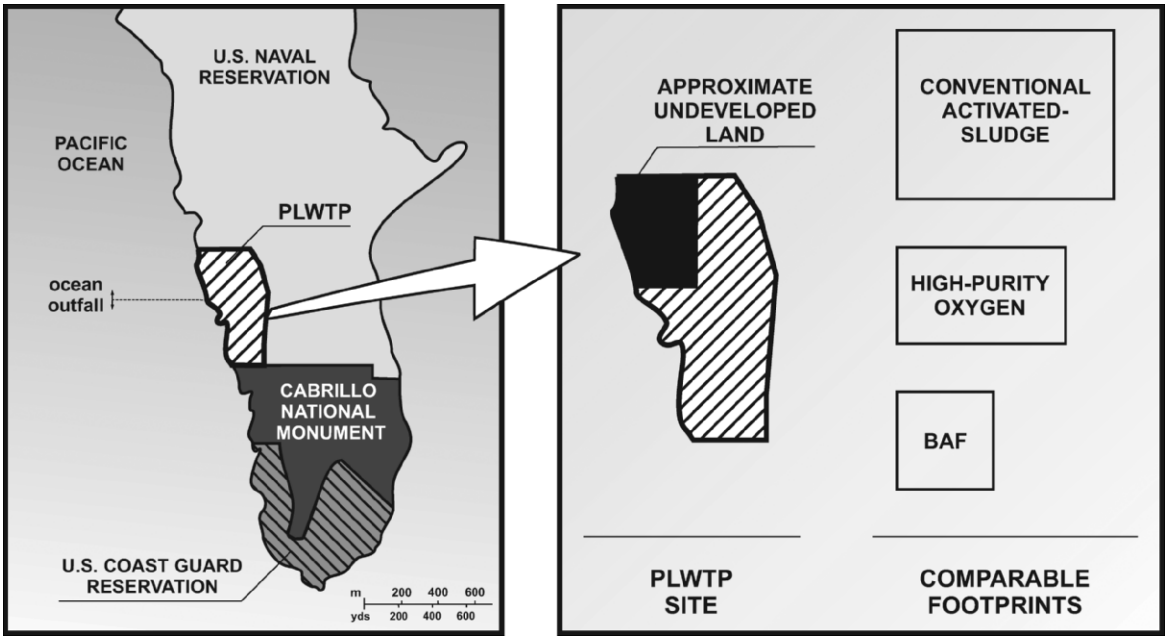

Figure 1—Location, land constraints, and approximate sizes of upgrading options for the PLWTP in San Diego, California.

tall × 0.2 m diameter) with media and biofilm when compared with columns with media only. Fujie et al. (1992), in their 1.2-m-high BAF pilot plant, noted higher transfer rates in columns with biofilm-free media compared with columns without media. They also noted a decline in oxygen-transfer rate with increasing biofilm concentrations and attributed the reduction to bubble coalescence caused by biofilms.

Oxygen balances on BAF pilots previously showed the difficulty of predicting OUR. For example, Harris et al. (1996) observed a difference as high as 54% between OUR and the oxygen requirements, as calculated from stoichiometry. The difficulty probably arises from the inability to accurately define the biofilm thickness and mass and from estimating the solids loss in the effluent and resulting from endogenous respiration. Also, the time to reach steady-state biofilm mass is not known, which means that previous studies may have been performed with changing biomass. Results documenting the performance of the Point Loma pilot plants and their success in meeting secondary treatment goals have been provided previously by Newman et al. (2005). They documented removal rates and process economics as a function of the loading rate. The process was judged as a viable alternative for meeting secondary treatment goals, although they cited the need for more research to better understand biosolids production rates. Here, we complement their paper with additional information on testing methodology and oxygen-transfer efficiency (OTE, %), as follows:

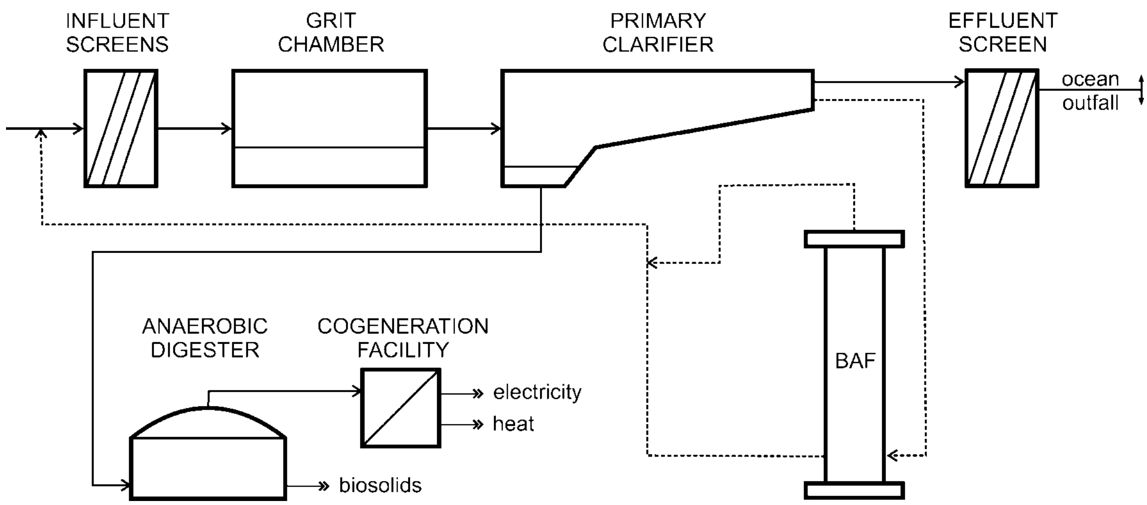

Figure 2—Process layout. The existing process is drawn with solid lines, and the dashed lines represent the chemically enhanced primary effluent being partially diverted to the BAF.

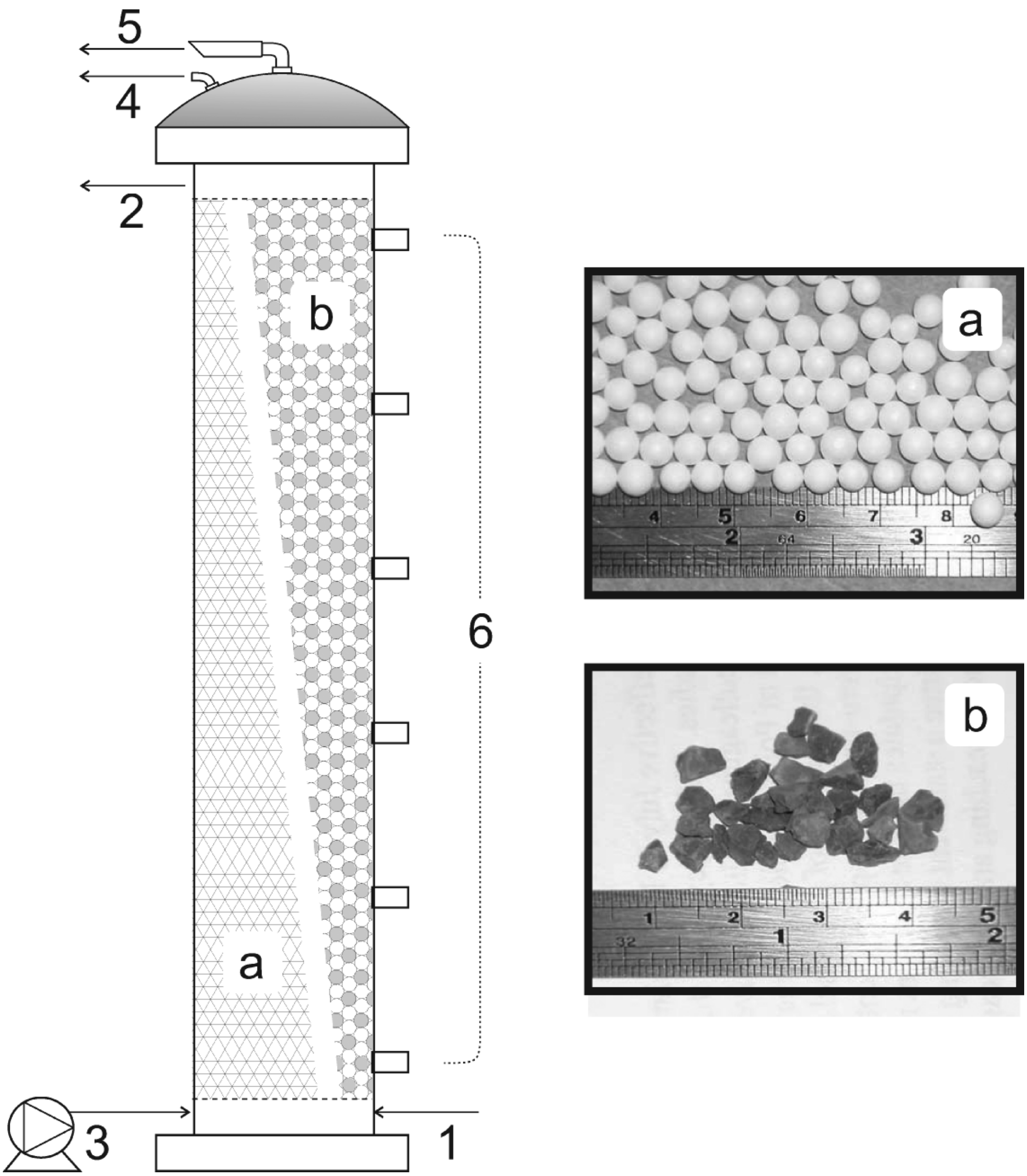

Figure 3—Schematics of the BAF columns: (a) Biostyr media, (b) Biofor media, (1) primary effluent, (2) secondary effluent, (3) air inlet, (4) manometric line (for offgas testing only), (5) air outlet, and (6) liquid sampling ports. Scales are both in inches and centimeters.

$$OTE = \frac{O_{2,TRANSFERRED}}{O_{2,SUPPLIED}} \quad (1)$$

Leung et al. (2006) have also reported oxygen-transfer rates in bench- and pilot-scale BAFs, but did not use the offgas method. This paper represents the first independent offgas testing on a full-depth BAF.

Materials and Methods

Figure 3 shows a schematic of the BAF columns, with details showing the different media used. Biostyr systems use Styrofoam spheres approximately 4 mm in diameter (Figure 3a). This medium has a lower specific gravity (ratio of medium density to the density of water) than water and was used in an upflow configuration. In upflow mode, a plenum, with equally spaced nozzles to trap the media, was used to retain the media particles. The Biofor filter is an upflow biological filter (Pujol et al., 1994) with a rock media, with specific gravity of 1.5 and a size distribution of approximately 3 to 5 mm (Figure 3b). Because this medium has specific gravity higher than water, it is typically chosen for upflow configurations. Careful screening (2.5-mm openings) of the influent is required to prevent clogging, as the influent is distributed through nozzles. For both columns, the media height was approximately 3.6 m (12 ft).

The total height was approximately 4 m (13 ft) for both columns, with sampling ports distributed along the column height. The Biofor

Table 1—Process influent and effluent parameters.

Parameter (all units in mg/L)	Influent	Biofor effluent	Biostyr effluent
BOD_{total}	98	31	21
$BOD_{carbonaceous}$	79	4	12
$BOD_{soluble}$	73	16	7
COD	203	41	67
$COD_{grab\ sample}$	207	71	76
TKN-N	35	16	31
NH_4-N	29	13	26
NO_3-N	0.2	12	0.5
TSS	41	9	20
$DOC_{grab\ sample}$	67	14.3	14.3

column was equipped with 4 sampling ports at 0.3, 1.2, 2.4, and 3.6 m from the bottom (i.e., 0.8, 4.0, 8.0, and 12 ft). The Biostyr column was equipped with 6 sampling points at 0.3, 0.6, 1.2, 1.8, 2.4, 3.0, and 3.6 m from the bottom (i.e., 0.8, 2.0, 4.0, 6.0, 8.0, 10, and 12 ft). For both columns, the first and last sampling ports corresponded to the inlet and outlet flows. Additional details on the column configurations are available in Newman et al. (2005).

Oxygen-transfer efficiency was evaluated to validate manufacturers' claims and to provide data to support a full-scale design. The OTE was measured using the offgas method (Redmon et al., 1983). This technique is based on performing an oxygen-purity measurement on the offgas stream leaving the top of the biological reactor and on performing a mass balance between the air feeding line and the offgas. We used an offgas analyzer by Ewing (Aerator-Rator Mark V, Ewing Engineering, Milwaukee, Wisconsin), which includes a Teledyne oxygen-purity meter (model 320BRC, Teledyne Analytical Instruments, City of Industry, California). The American Society of Civil Engineers (Reston, Virginia) (ASCE) has a standard guideline for process-water testing, and the offgas method is the most commonly used method (ASCE, 1997). One of its important advantages is its independence of process conditions, such as the dissolved oxygen (DO) concentration in the aeration tank. Typically, offgas testing is performed on activated sludge aeration basins and has become the method of choice for testing of diffused aerators. Floating hoods, with capture areas ranging from 2 to 5 m^2, are typically used and are placed in various locations on the surface of an aeration tank (generally to cover more than 2% of the surface area), to obtain time- and space-averaged oxygen-transfer rates.

With a relatively small diameter, the BAF columns tested here had the advantage of having readily available the entire column cross-sectional area for testing. The offgas method was applied to the pilot plants by covering the top of the column and capturing 100% of the offgas. In this way, the measurement produces the actual oxygen-transfer rate within the entire reactor, not just at a measured point. The top of the column in Figure 3 shows the arrangement for testing. Each column (0.61 m and 0.66 m diameter for Biofor and Biostyr, respectively) was covered with two layers of 0.25-mm (1/100 in.) construction plastic liner, and all other gas release points were sealed. In this way, the offgas was forced to exit through the sampling point at the top of the column. An important feature of this arrangement was the development of a small positive pressure of a few centimeters of water column under the construction plastic. This caused the plastic to bulge outward and ensured that leaks, if any, would be leaks of offgas to the atmosphere. Such leaks would not affect the transfer-efficiency measurement, unlike air leaks into the columns. This increased pressure was recorded in the analyzer, and the increase is too small to affect the oxygen saturation concentration significantly.

Testing was performed on three pilot columns (Biofor-C, Biofor-N, and Biostyr), with the Biofor and Biostyr columns optimized for meeting the carbonaceous requirements of secondary treatment (i.e., 85% removal of BOD and total suspended solids [TSS] or 30 mg/L in the effluent, whichever is less). The Biofor-N column performance has been described (Newman et al., 2005) and was found unnecessary to meet carbonaceous treatment objectives. Oxygen-transfer testing was not performed on this column during this study. Testing was performed at the expected design conditions and over a range of air flowrates that spanned the design point. Dissolved oxygen concentrations were measured at all sampling ports along the column height, to convert the observed OTE to process-standard OTE (αSOTE, %), as described by the ASCE (1997) standard guidelines. The dissolved oxygen was measured with a YSI model 58 DO meter (Yellow Springs Instruments, Yellow Springs, Ohio). Dissolved organic carbon (DOC) and total (unfiltered) chemical oxygen demand (COD) were measured as a function of column height. The DOC was measured using a Tekmar-Dohrman Apollo 9000 (Cincinnati, Ohio) analyzer, and samples were filtered through a 0.7-μm glass fiber filter. A mass balance was performed to relate measured OTE to transfer rates expected from the COD or DOC removal rate. Table 1 shows the process conditions during the testing. Only the Biofor column was partially nitrifying during the testing. To determine if the oxygen-transfer results were consistent with the oxygen demand being removed from the influent, a mass balance was performed, as in eq 2.

$$\begin{aligned} OUR = Q[&COD_{in} - COD_{out} + DO_{in} - DO_{out} \\ &+ 4.5(NH_4 - N_{in} - NH_4 - N_{out})] \\ &- COD_{\substack{converted \\ to\ cell\ mass}} \end{aligned} \tag{2}$$

Where

OUR = oxygen uptake rate ($M_{O2,uptake}/T$).

The oxygen transfer rate (OTR, $M_{O2,transferred}/T$) is calculated as follows:

$$OTR = AFR \cdot w_{O_2} \cdot OTE \tag{3}$$

Where

w_{O2} = weight fraction of oxygen in air = 23% w/w, and
AFR = air flowrate (L^3/T).

The units must be consistent for the two equations. For eq 3, a conversion factor commonly used in the United States, noted in the ASCE standard (2007), is 1.036 lb/h/scfm, if the air flowrate is expressed in standard cubic feet per minute, OTE expressed as a fraction, and OTR expressed in pounds per hour.

Results and Discussion

Figures 4 and 5 show the results as height profiles for Biofor and Biostyr, respectively. The graphs show trends related to liquid and gas flowrates. The DOC and COD decline with increasing height, as expected. The only deviation from the trend is the first point above the feed point in the Biofor column, which had higher COD and must be caused by sloughed biosolids, because the DOC did not have a corresponding increase.

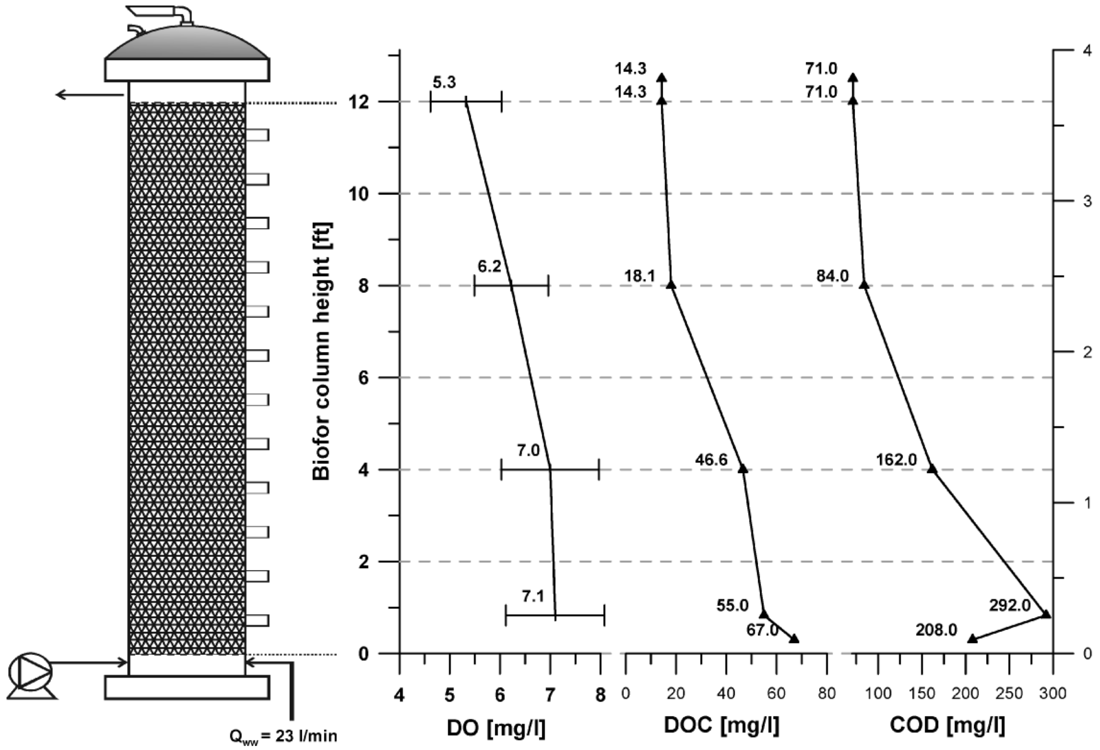

Figure 4—Height profiles for the Biofor column. The dissolved oxygen is the average of four measurements per experiment, and the error bars represent 1 standard deviation. For the DOC and COD, labels represent actual values for each point.

The OTE declines with increasing gas flowrate, which is an expected result. At some lower value of gas flowrate, depending on process conditions, the dissolved oxygen concentration begins to decline and, at extremely low gas flowrates, may become limiting.

It appears that adjusting process conditions to standard conditions for oxygen transfer, as described in the ASCE standard (2006), may not be appropriate for the BAF process. In adjusting to standard conditions, the ASCE standard assumes that the dissolved oxygen concentration is homogenous throughout the aeration zone. In the case of BAFs with low air flowrates, this is unlikely to be true. In fact, the varying oxygen demand along the height of the BAF may create oxygen-limited conditions in one area, with adequate or excess oxygen in other areas. At low air flowrates, the mixing provided by air bubbles may be insufficient to mix the reactor well, and a plug-flow-reactor model may be more appropriate to describe the hydraulic regime in the BAF. Using a simple average dissolved oxygen concentration for correction, which is generally acceptable for other types of aeration processes, may not be acceptable for this situation. An alternative may be to use the lowest observed dissolved oxygen concentration for adjusting to standard conditions. We used this procedure, and it ensures that all parts of the column will have sufficient dissolved oxygen, if standard conditions are used for design.

Figure 6 shows efficiencies that are higher than typically achievable at the same process-water depth with fine-pore aeration systems. Table 2 summarizes the results for both columns. Peak OTE was approximately 8.0%/m (2.4%/ft), and peak αSOTE was approximately 13%/m (4%/ft), which compares quite favorably to fine-pore diffuser efficiencies. Rosso and Stenstrom (2005) reported average values of αSOTE of 3%/m for fine-pore diffusers, with values reaching 5%/m for new diffusers at longer mean cell residence times (>10 days). This high rate in the BAF is obtained without using a small gas-release orifice typical of fine-pore-aeration devices.

The higher transfer efficiency is likely the result of the bubble residence time in the column, which is increased because of gas holdup in the media. The Biostyr column had an observation port, and, in the early part of the study, it was possible to observe gas bubbles being retained on the media for a few seconds. Bubbles could be seen moving upward under the influence of turbulent flow, then attaching or being captured for several seconds among media particles, and then being sheared away and replaced by new bubbles. This bubble retention provides additional contact time for gas transfer, which is believed to account for the high transfer efficiency. The bubble sizes are clearly larger than observed for fine-pore diffusers; therefore, the increased transfer rate is not the result of bubble diameter. The media shape (spheres in the Biostyr and irregular shapes in the Biofor) may have an effect on gas holdup, but this effect could not be evaluated.

Table 3 shows the results of applying these equations for each test for both columns. In the case of nitrification, a value of 4.5 mg O_2/mg NO_3^- produced was used to calculate the oxygen required for nitrification. No denitrification was assumed or observed. The fractional conversion of COD to cells is typically called the heterotrophic yield, Y_H, and ranges from 0.3 to 0.7, depending on the sludge age of the system and the substrate being treated. A heterotrophic yield of 0.5 was used for the analysis. In the case of nitrification, the yield represents the fraction of ammonia that is

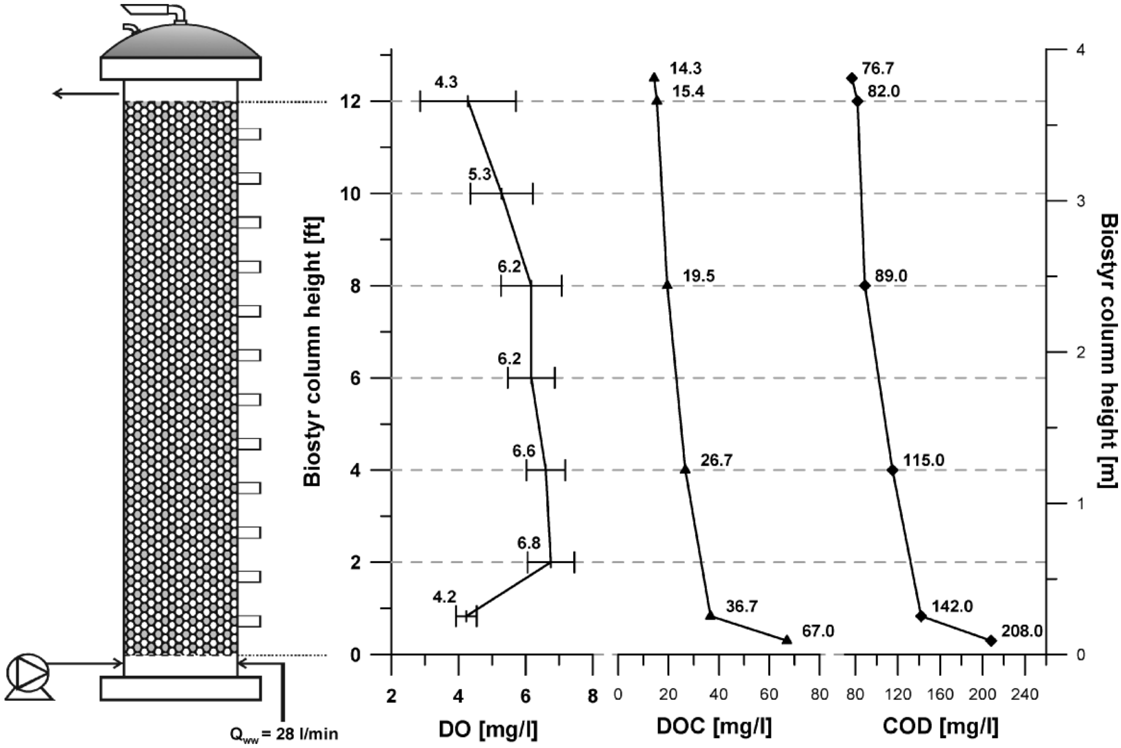

Figure 5—Height profiles for the Biostyr column. The dissolved oxygen is the average of six measurements per experiment, and the error bars represent 1 standard deviation. For the DOC and COD, labels represent actual values for each point.

needed for cell synthesis, which is too low to be of significance for this experimental condition. The Biofor mass balances agree, on average, within 8%. The difference for the Biostyr is greater, averaging 43%, with the mass balance predicting lower transfer than the offgas measurements. Mass balances to estimate oxygen-transfer rates are reported to be effective over a short time (Osorio and Hontoria, 2006), but the ASCE (2006) process-water-testing guidelines describe material-balance methods for estimating oxygen transfer values as rough approximations.

Our results are consistent with the ASCE testing guidelines and are likely caused by the extended period required for the biomass retained in the column to acclimate to new conditions. The OURs calculated from the mass balances do not accurately predict the oxygen-transfer rates for both reactors. The oxygen transfer rate in

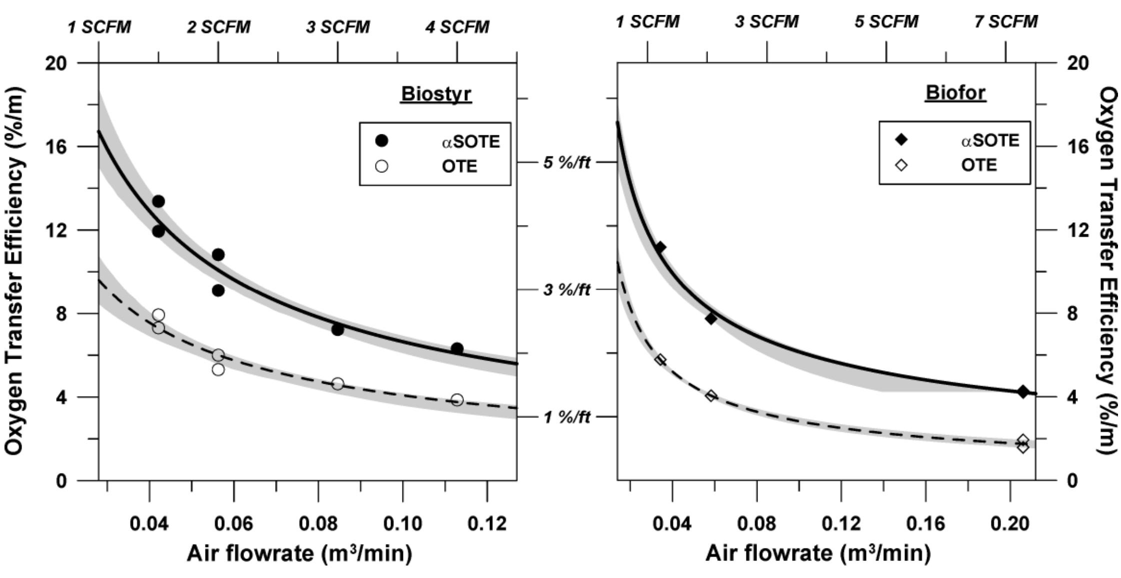

Figure 6—Oxygen-transfer efficiency and αSOTE at different air flowrates for both columns. Trend lines are power fits, and shaded areas are 85% confidence intervals. English units are italicized.

Table 2—Summary of oxygen-transfer-test results. For both OTE and αSOTE, the average and standard deviation are calculated.*

		Q		AFR		OTE		SOTE		OTE/Z		SOTE/Z	
	Test No.	gpm	L/min	scfm	L/min	Average %	Standard deviation %	Average %	Standard deviation %	Average %/m	Average %/ft	Average %/m	Average %/ft
Biofor	1	6.2	23	7.3	207	5.8	0.2	15.7	0.5	1.59	0.48	4.29	1.31
	2	6.2	23	7.3	207	7.1	0.4	15.4	0.8	1.94	0.59	4.21	1.28
	3	6.2	23	2.1	59	14.8	0.1	28.3	0.1	4.05	1.23	7.74	2.36
	4	6.2	23	1.2	34	21.1	0.8	40.8	1.5	5.77	1.76	11.2	3.40
Biostyr	1	7.4	28	2.0	57	19.4	0.4	33.3	0.6	5.30	1.62	9.10	2.78
	2	7.2	27	2.0	57	21.9	0.1	39.6	0.3	5.99	1.83	10.8	3.30
	3	7.4	28	1.5	42	26.7	0.2	43.7	0.3	7.30	2.23	11.9	3.64
	4	7.3	28	1.5	42	29.0	0.3	48.9	0.5	7.93	2.42	13.4	4.08
	5	7.4	28	3.0	85	16.9	0.1	26.4	0.1	4.62	1.41	7.22	2.20
	6	7.4	28	4.0	113	14.1	0.2	23.1	0.1	3.85	1.18	6.32	1.93

* Key: Q = liquid flowrate, AFR = air flowrate, and Z = column height.

the Biostyr column is greater than the calculated uptake rate, for all test conditions. For the Biofor column, the mass balance is more accurate and underestimates OUR for high air flowrates and overestimates OUR for low air flowrates. Note that the average influent and effluent COD and nitrate concentrations were used, and, if they varied from test to test, it would affect the mass balance.

Dissolved Oxygen and Transfer Efficiency Monitoring Recommendations. The ASCE methodology, which is generally based on the assumption of complete mixing, has been used to describe aeration in plug-flow regimes (Boyle et al., 1989). The procedure was to divide the volume of the tank or reactor being aerated into zones and treat each zone independently, with respect to mass-transfer rates and dissolved oxygen concentration. In this way, Boyle et al. (1989) were able to show that the ASCE method for clean-water testing and offgas results for process-water testing produced virtually identical results, when compared with radiotracer and mass-balance methods. A natural consequence of this procedure would be to base the conversion from standard to process conditions on the minimum dissolved oxygen concentration observed over the height of the column. In this way, if a clean-water-transfer rate (i.e., standard oxygen transfer efficiency, SOTE, %) is used to calculate a process-water rate, the column dissolved oxygen concentration will always exceed the required dissolved oxygen concentration. For example, Biostyr test 4 used the lowest air flowrate (42 L/min or 1.5 scfm) and, as a consequence, had the lowest dissolved oxygen concentrations at the bottom of the column, where the oxygen demand is highest. Figure 5 shows that, even at the low air flowrate, the dissolved oxygen profile was adequate in the lower portions of the column and was similar to tests at higher air flowrates. In the upper portion of the column, the dissolved oxygen profile was more variable and was below 2 mg/L in one case, hence the larger error bar in Figure 5. The αSOTE was 49% using the average dissolved oxygen concentration. Using the minimum dissolved oxygen of 1.6 mg/L produces 34% αSOTE, which is a more conservative design value and would ensure that the top of the column would have 1.6 mg/L dissolved oxygen for the same conditions. If 49% αSOTE were to be used, the top of the column would operate at a lower dissolved oxygen concentration and may be too low for optimal treatment. If the αSOTE results are recalculated using 5 mg/L for the Biofor and 4.0 mg/L for the

Table 3—Mass balance on COD compared with oxygen-transfer results (see eqs 1 and 2 for the calculation procedure).

	Liquid side								Gas side				Mass balance
			Influent		Effluent								
	Q		COD	NO_3-N	COD	NO_3-N	DO	OUR	AFR		OTE	OTR	Difference
	gpm	L/min	mg/L	mg/L	mg/L	mg/L	mg/L	g/h	scfm	L/min	%	g/h	%
BioStyr	7.4	28	210	0.2	77	0.5	4.7	122	2.0	57	19.4	183	−33
	7.2	27	210	0.2	77	0.5	4.7	119	2.0	57	21.9	206	−43
	7.4	28	210	0.2	77	0.5	4.0	121	1.5	42	26.7	189	−36
	7.3	28	210	0.2	77	0.5	1.6	115	1.5	42	29	205	−44
	7.4	28	210	0.2	77	0.5	5.0	122	3.0	85	16.9	239	−49
	7.4	28	210	0.2	77	0.5	5.7	124	4.0	113	14.1	265	−53
Biofor	6.2	23	210	0.2	71	12	5.9	182	7.3	207	5.8	197	−8
	6.2	23	210	0.2	71	12	5.6	181	7.3	207	7.1	243	−25
	6.2	23	210	0.2	71	12	5.5	181	2.1	59	14.8	144	26
	6.2	23	210	0.2	71	12	4.8	180	1.3	37	21.1	129	39

* Key: Q = liquid flowrate, AFR = air flowrate, and OUR = oxygen uptake rate.

Biostyr minimum dissolved oxygen concentrations, which are conservative, the αSOTE declines to 95% of the values shown in Figures 2 and 3, on average. Our recommended design approach is to use the more conservative values for αSOTE, based on the minimum dissolved oxygen concentration.

In the case of operating a system with dissolved oxygen gradients, such as a BAF, which cannot be described well by the completely mixed reactor assumption, an oxygen-transfer-monitoring system may be more suitable than a dissolved oxygen monitoring for process control. Dissolved oxygen probes return a point value, thus describing a section of the reactor, while oxygen-transfer-measuring devices (such as offgas analyzers) report the transfer over the entire reactor volume. With a little experience in operating a BAF, a general range of OTEs appropriate for normal operation can be developed and can account for site-specific conditions. The offgas measurement of OTE, coupled with the air flowrate, can be used to calculate the OUR. Therefore, the offgas measurement provides both the transfer efficiency and the OUR and functions as a respirometer. The offgas measuring device has intrinsic advantages over dissolved oxygen probes. Only a single sensor is required for offgas analysis, and the sensor makes no contact with the wastewater and therefore does not foul. The sensor should be maintenance-free, except for occasional fuel-cell replacement. Furthermore, a single offgas analyzer, located centrally in a convenient location, can be multiplexed with several hood locations or BAFs. This is possible, because there is no reaction in the gas, and the time of travel does not affect the efficiency or the calculated OTE. Dissolved oxygen concentration and uptake can vary rapidly with time (i.e., 2 mg/L dissolved oxygen would be consumed in 2 minutes of travel time with 60 mg/L · h OUR). Because BAFs are typically operated as modular units to facilitate backwashing, a single offgas analyzer could monitor the performance of many units.

Comparison of Clean-Water with Process-Water Transfer Rates. Previous studies (Eckenfelder and Ford, 1968; Reiber and Stensel, 1985) have observed greater oxygen-transfer rates in process water than in clean water, and some have proposed alpha factors greater than 1.0. Some have also suggested enhanced transfer resulting from interactions between the biofilm and the liquid films surrounding the bubbles. Such enhanced transfer has been called *chemosorption* and can be observed when aerating catalyzed sodium sulfite (Danckwertz, 1951). Previous observations of chemosorption in biological systems have been attributed to measurement error, because there are systematic errors associated with measuring OUR and oxygen-transfer rate (Mueller and Stensel, 1990). Also, there is little, if any, probability that biological flocs, which are 100 to 600 μm in diameter, or biofilms, which can be even thicker, can react and affect the dissolved oxygen gradient in the mass-transfer films, which have thickness of approximately 1 μm or less.

The increased rate of transfer in BAFs is attributed to gas holdup, which has been readily observed. Leung et al. (2006) have shown that mass-transfer rates triple for a doubling of gas holdup volume. They also show that gas holdup increases with increasing gas velocity. The media, when coated with a biofilm, will have lower porosity and increased gas velocity, increasing relative holdup. This is the likely mechanism for the observed increases in process-water-transfer efficiency in the presence of media and biomass.

The increase in transfer in the presence of media or biofilm should not be characterized with the alpha factor. The alpha factor has traditionally been used to quantify the reduction in transfer rate because of the presence of surfactants (Stenstrom and Gilbert, 1981). Nevertheless, it should not be used to describe the increase observed in BAFs, because there is no need to lump wastewater effects on gas transfer and relative gas holdup in the same parameter. A better mechanism is to correlate improvements in process-water-transfer efficiency αSOTE with increased gas holdup. This approach might become practical and more accurate than using alpha factors when additional research is performed.

Conclusions

Oxygen-transfer testing of two pilot-scale biological aerated filters (Biofor and Biostyr) was performed at the PLWTP. The purpose of the testing was to determine the oxygen-transfer rates to assist in the overall evaluation of the BAFs. This is the first independent offgas testing on a full-height BAF using actual wastewaters.

The following conclusions were drawn from this work:

(1) The OTEs of the Biofor column (4 to 6%/m) were as good or better as one might expect from a typical fine-pore aeration system (3 to 5%/m) treating similar flows at similar depths. The improved transfers are likely the result of bubble holdup time in the media, and bubble holdup was observed in a BAF column with an observation port.

(2) The dissolved oxygen concentration in each column decreased with increasing height. For one test condition at low air flowrate, the dissolved oxygen concentration at the top of the one column decreased to 1.6 mg/L, even though, in the lower parts of the column, the dissolved oxygen was more than 5 mg/L. This suggests that the minimum dissolved oxygen in the column be used for converting process-water oxygen-transfer rates to clean-water rates.

Liquid- and air-side mass balances were performed to see if the gas-transfer rates matched the removal of oxygen demand in the BAFs. The liquid-side balance used influent and effluent COD and typical values of cell yield. The mass balances for one column were relatively close (8% average difference). The match for the other column was poorer, with the liquid-side balance showing 43% more transfer than observed in the offgas testing. This may be caused by the insufficient time to achieve liquid-side equilibrium.

Submitted for publication June 25, 2007; revised manuscript submitted October 11, 2007; accepted for publication January 25, 2008.

The deadline to submit Discussions of this paper is October 15, 2008.

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