Fifteen Years of Offgas Transfer Efficiency Measurements on Fine-Pore Aerators: Key Role of Sludge Age and Normalized Air Flux

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ABSTRACT: Fine-pore diffusers, often called fine-bubble diffusers, have nearly replaced coarse bubble diffusers in municipal wastewater treatment over the past 20 years. The rapid increases in energy costs, which began in the 1970s, created financial incentives to upgrade to this more expensive and maintenance-intensive method of aeration. Fine-pore diffusers have the added benefit of reducing volatile organic compound stripping and reduced aeration heat loss. This paper summarizes 15 years of oxygen transfer efficiency measurements using the offgas technique. Efficiencies are shown for different types of diffusers at various tank geometries (depth, diffuser size, and number), airflow rates, and mean cell retention times (MCRT or sludge age). By normalizing the airflow rates per unit of depth and diffusing area, efficiencies measured in different plants can be compared. The results show that aeration efficiencies are logarithmically related to the ratio between MCRT and the normalized air flux, with transfer rates suppressed by low MCRT or high normalized air flux systems. There is no evidence for different α factors among the different types of fine-bubble diffuser types. *Water Environ. Res.,* **77,** 266 (2005).

KEYWORDS: aeration, oxygen transfer, fine pore, fine bubble, normalized air flux, wastewater.

Introduction

Fine-pore diffusers are now the most commonly used diffusers in wastewater treatment in the United States and Europe. They have higher efficiencies on the basis of energy consumption (standard aeration efficiency [SAE], measured in lb O_2/hp-hr or kg O_2/kW-hr). They are routinely used in full floor configurations, which take maximum advantage of their efficiency. Fine-pore diffusers are a subset of fine-bubble diffusers; fine-pore diffusers make their small bubbles by releasing compressed air through small orifices or pores in either punched membranes or porous material, such as ceramic stones or sintered plastic. Other aeration equipment, such as submerged turbines or jet diffusers can also create fine bubbles, but do so without using small orifices; in both cases mechanical energy is used to shear large bubbles into fine bubbles. Fine-pore diffuser systems strip the fewest volatile organic compounds by virtue of their increased efficiency, which results in lower airflow rates (Hsieh et al., 1993a and b). Fine-pore diffusers also have reduced heat losses for the same reason (Sedory and Stenstrom, 1995; Talati and Stenstrom, 1990).

Fine-pore diffusers have two important disadvantages: the first is the need for periodic cleaning; the second is large negative effect on transfer efficiency from wastewater contaminants, which is most often quantified by the α factor (ratio of process water to clean water mass transfer coefficients, or K_La_{pw}/K_La_{cw}). Fine-pore diffusers generally have lower alpha factors than coarse-bubble diffusers or surface aerators for similar conditions (Stenstrom and Gilbert, 1981). Differences in α factors among aeration systems were first noted in the 1930s (Kessner and Ribbius, 1935), but were generally forgotten until the early 1980s, when fine-pore diffusers became popular again.

Many plants were initially designed with α factors of 0.8, which resulted in inadequate aeration systems and considerable controversy among competing manufacturers. An α factor of 0.8 was commonly used before the 1980s as a ''universal'' α factor for all types of aeration systems, including surface aerators.

Background

To better define aerator performance, offgas testing has been extensively used to measure diffused aeration efficiency. Offgas testing was developed by Redmon et al. (1983) in conjunction with the U.S. Environmental Protection Agency (EPA)-sponsored American Society of Civil Engineers (ASCE) Oxygen Transfer Standards Committee. This committee produced a fine pore manual (U.S. EPA, 1985), a clean water oxygen transfer standard (ASCE, 1984, 1991) and guidelines for process water testing (ASCE, 1997). Clean water testing and offgas testing are described in detail in these publications. The net result of the improved testing methods is an increase in our accuracy and precision in designing and quantifying aeration systems.

The offgas method provides accurate and precise oxygen transfer measurement for diffused aeration systems (coarse, fine, turbines, and jets) at virtually all process conditions. The dissolved oxygen concentration or oxygen uptake rate does not interfere with the test procedure. Offgas testing of early fine-pore aeration systems reveals a wide range of α factors, from as low as 0.17 to 0.7 (Masutani and Stenstrom, 1990). As more data have become available, a general understanding has developed that the α factor is a function of mean cell retention time (MCRT), or sludge age. Fine-bubble aeration systems in activated sludge processes operating at low loading rates (i.e., high MCRT or low food-to-microorganism ratio (F/M) generally have higher α factors.

Literature studies (U.S. EPA, 1989) showed that the oxygen transfer efficiency is directly proportional to MCRT, inversely proportional to airflow rate, and directly proportional to geometry parameters (diffuser submergence, number, and surface area). The effect of MCRT relates to the degree of treatment and removal of oxygen transfer reducing contaminants, such as surfactants. The airflow rate influences the fluid dynamics of bubbles; the higher the airflow rate, the larger the bubbles, which creates lower surface-to-volume ratio and higher bubble rise velocity. The net result is smaller gas-to-liquid area and shorter bubble residence time, reducing mass transfer. Geometry affects the efficiency because,

Table 1—Locations: A = Northern CA: B = NV; C = Frankenmuth, MI (after Allbaugh and Kang, 1989); D, E = Green Bay, WI (after Marx, 1989); F = Hartford, CT (after Gilbert and Sullivan, 1989); G, H, I, J, K, L = Southern CA; M = Madison, WI (after Boyle et al., 1989); N, O = Milwaukee Jones Island, WI (after Warriner, 1989a); P = Milwaukee South Shore, WI (after Warriner, 1989b); Q = Southern CA; R = Ridgewood, NJ (after Mueller and Saurer, 1989); S, T = Southern CA; U = Central CA; V, W = Southern CA; X, Y, Z, = Northern CA

Plant Code	Diffuser Type	Diffuser Code	Diffuser Area (m^2/diff)
A	14″ ceramic discs	CDi	0.0856
B	9″ ceramic discs	CDi	0.0373
C	9″ ceramic discs	CDi	0.0373
D	9″ ceramic discs	CDi	0.0373
E	membrane tube	MT	0.0807
F	7″ ceramic domes	CDo	0.0438
G	membrane tube	MT	0.0807
H	9″ membrane discs	MD	0.0263
I	9″ ceramic discs	CDi	0.0373
J	membrane tube	MT	0.0807
K	7″ ceramic domes	CDo	0.0438
L	9″ membrane discs	MD	0.0263
M	7″ ceramic domes	CDo	0.0438
N	12″ ceramic plates	CP	0.0929
O	12″ ceramic plates	CP	0.0929
P	9″ ceramic discs	CDi	0.0373
Q	7″ membrane discs	MD	0.0159
R	7″ ceramic domes	CDo	0.0438
S	11′ × 4′ membrane panels	MP	4.0877
T	7″ ceramic domes	CDo	0.0438
U	14″ membrane discs	MD	0.0636
V	9″ ceramic discs	CDi	0.0373
W	7″ ceramic domes	CDo	0.0438
X	9″ ceramic discs	CDi	0.0373
Y	9″ membrane discs	MD	0.0263
Z	3′6″ × 11′7 3/8″ membr. panels	MP	3.7766

at greater submergence and tank coverages (ratio between diffusing area and total tank area), the mass transfer time and surface area are higher.

Test results for clean water testing can be reported as standard oxygen transfer efficiency (SOTE, %), standard oxygen transfer rate (SOTR, kgO_2/ hr), or standard aeration efficiency (SAE, kgO_2/kW-hr). Care must be exercised in using SAE because different power measurements can be made. Generally, "wire" power is preferable, which includes blower, coupling, and motor inefficiencies. Standard conditions are well-defined (ASCE, 1991) and correspond to 20°C, zero dissolved oxygen, mean atmospheric pressure, and zero effect of water salinity or other contaminants (e.g., α factor = 1.0, β factor = 1.0). For process water tests, results are reported as oxygen transfer efficiency (OTE), oxygen transfer rate (OTR), and aeration efficiency (AE), which contain the effects of nonstandard conditions. For offgas results, it is convenient to use αSOTE, or αSOTR; these two parameters are corrected for all nonstandard conditions except the α factor. This is convenient because the other nonstandard conditions are easily measured and corrected. The α factor can be calculated from offgas results if clean water data are available. In this paper, αSOTE will be used to refer to process water transfer efficiencies. To compare the results presented here to actual process conditions, the other corrections, such as dissolved oxygen and temperature must be applied.

With fine-pore diffusers, the efficiency is also affected by the condition and age of the diffusers (Iranpour et al., 2000a and b, 2001, 2002). Membrane diffusers can harden or soften after use, resulting in increased pressure loss or increased bubble diameter. Ceramic diffusers can foul with biological material or scale with inorganic precipitates, which also increases bubble diameter. To account for this phenomenon, a modified α factor was introduced, called the αF factor. In practice, the αF factor refers to a system that has been in service long enough for diffuser performance to be degraded by fouling, scaling, or wear. The reduction in transfer efficiency because of fouling (e.g., the F part of the αF factor) can be large, depending on the diffuser maintenance program. In the authors' experience, reductions of 30 to 50% in transfer rates can be observed for unmaintained diffusers; reductions as little as 10% have been observed for well-maintained diffusers.

Plant-Scale Results

To quantify background relationships and test other hypotheses, offgas test results measured by the senior author over the past 17 years, and the ASCE-sponsored studies (U.S. EPA, 1985), were compiled and analyzed. The dataset is based on 30 plants nationwide and 372 different flux-averaged offgas measurements. For some plants, many replicate tests were performed. Because of some missing values, the number of available data for the different statistical analysis was limited to 363. All the plants were treating municipal wastewater, with few exceptions, where minor percentages of food industry waste were also present. A wide range of diffuser ages and models (ceramic discs, domes and plates, membrane discs, tubes, and panels) was encountered. The diffuser submergence ranged from 3.75 to 7.32 m. Table 1 summarizes the existing plant conditions.

Fifteen parameters were observed and divided in five main groups: (1) efficiency (OTE, αSOTE and α), (2) sludge age (MCRT and load F/M), (3) airflow rate per diffuser, (4) geometry (tank area, diffusers number, type, model, and submergence), (5) additional information (time in operation, presence of industrial waste, dissolved oxygen, cleaning method, and fouling history). The 363 available measurements of the standardized efficiency in process water (αSOTE) showed a wide range of values, from 4.66 to 24.81%. The 232 available alpha values varied from 0.22 to 0.79, were highly variable, and well-represented by the assumed value of 0.8, as noted earlier. No evidence was found for a particular type of diffuser having higher or lower alpha values; all diffuser types were found over the range of measured alpha values.

Among the five main groups of parameters, sludge age, airflow rate per diffuser, and geometry were correlated with transfer efficiency. The correlation between diffuser submergence and total diffusing area confirm background studies (U.S. EPA, 1985). Figure 1 shows the relationship between transfer efficiency, as indicated by αSOTE or α factor, and MCRT or specific airflow rate. Figure 1 is restricted to the authors' observations and is a subset of the data analyzed later.

A large range of MCRTs was observed, from as low as 1.6 to as high as 36 days. In all cases, the MCRT was calculated without considering the mixed liquor suspended solids (MLSS) contained in the secondary clarifiers. The observations are scattered around

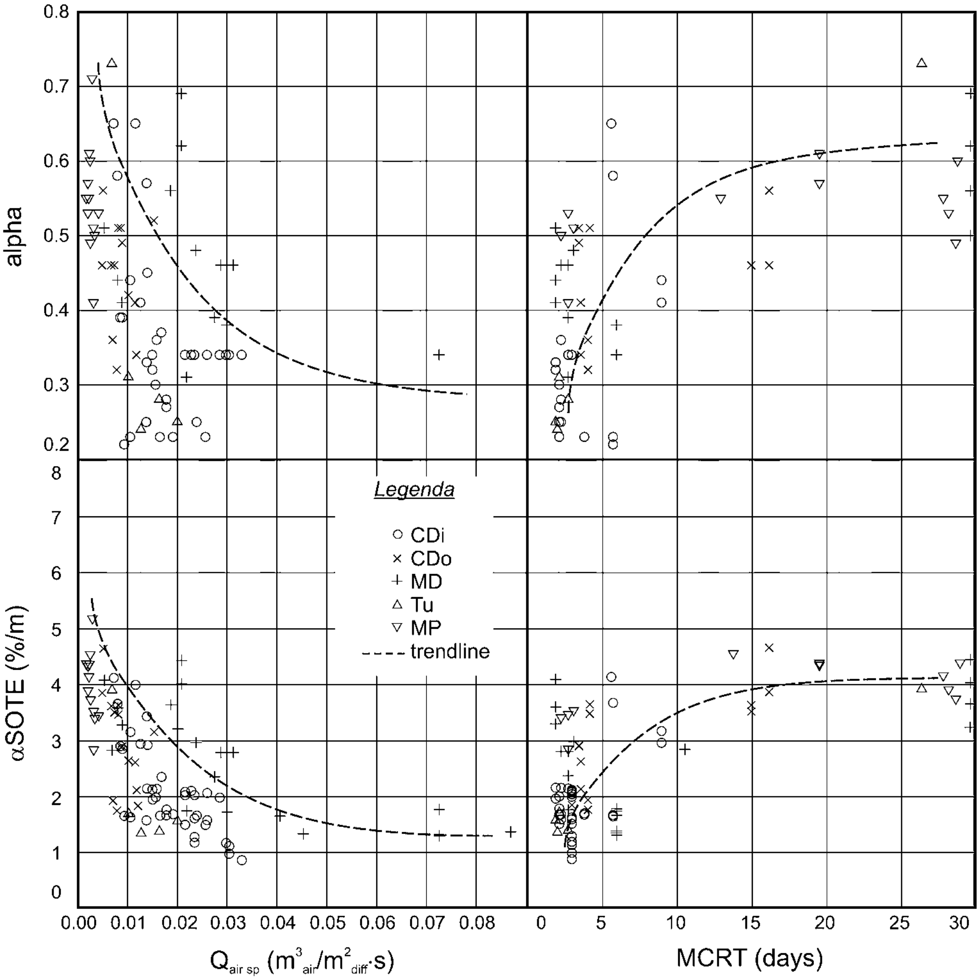

Figure 1—Efficiency parameters versus specific air flux and MCRT for a subset of data (plants A, B, H, I, J, K, L, Q, S, T, U, V, W, X, Y, and Z in Table 1). CDi: ceramic discs; CDo: ceramic domes; CP: ceramic plates; MD: membrane discs; Tu: ceramic, plastic, and membrane tubes; and MP: membrane panels.

a general trendline. The scatter represents various uncontrolled factors, such as diffuser age and condition. In some cases, plants kept sufficient diffuser maintenance records, but the records are too few or inconsistent; hence, they are unsuitable for statistical analysis. Nevertheless, in some cases, variability can be explained by diffuser conditions. For example, the ceramic discs (open circles) in Figure 1 are generally older, mature diffusers with greater fouling. The membrane discs (plus symbols) in the same figure with high alpha factors were known to be new or recently cleaned.

In one case, a single plant had two parallel, independent treatment systems (i.e., parallel aeration tanks with separate clarifiers and return sludge systems) with identical diffusers. One side was operated at low MCRT, and the other side was operated at high MCRT to produce water for reclamation. Figure 2 shows the transfer efficiency of the two sides, which remarkably illustrates the effect of MCRT. This plant was later tested when the two sides were operated at the same MCRT, and identical transfer efficiencies were observed.

To better understand the effects of MCRT and airflow rate, the diffuser types and other site-specific conditions were analyzed. Airflow rate per diffuser was normalized as flow per unit of active diffuser surface area and per unit of depth, i.e., specific air flux per unit of depth, thus accounting for the effects of tank geometry. Diffusers-specific areas were measured in the laboratory, where the same diffuser types and models as in the dataset were available. In this procedure, only the actual bubbling or active area was considered, i.e., bolt and retainer areas were subtracted for ceramic and plastic discs, domes, and tubes. For membrane discs and tubes, only the punched areas were included, without considering the dead spaces between them. Panels were considered in their entirety, because of the negligible surface of the top frame area.

We also performed regressions of airflow per diffuser and diffuser density as a function of tank floor area, which are frequently used parameters in clean water testing and diffuser design. Airflow per unit of active diffuser area had higher correlation. Intuitively, this makes sense, because airflow per unit of active diffuser area includes the effect of airflow per diffuser, and diffuser per unit area of tank bottom. Systems with higher airflow per unit of active area also have lower diffuser density (hence the need for higher airflow). Introducing the second parameter of diffuser density as a function of tank area adds another variable to the regression and makes it more complicated. The analysis of our data did not show improvement in adding this parameter.

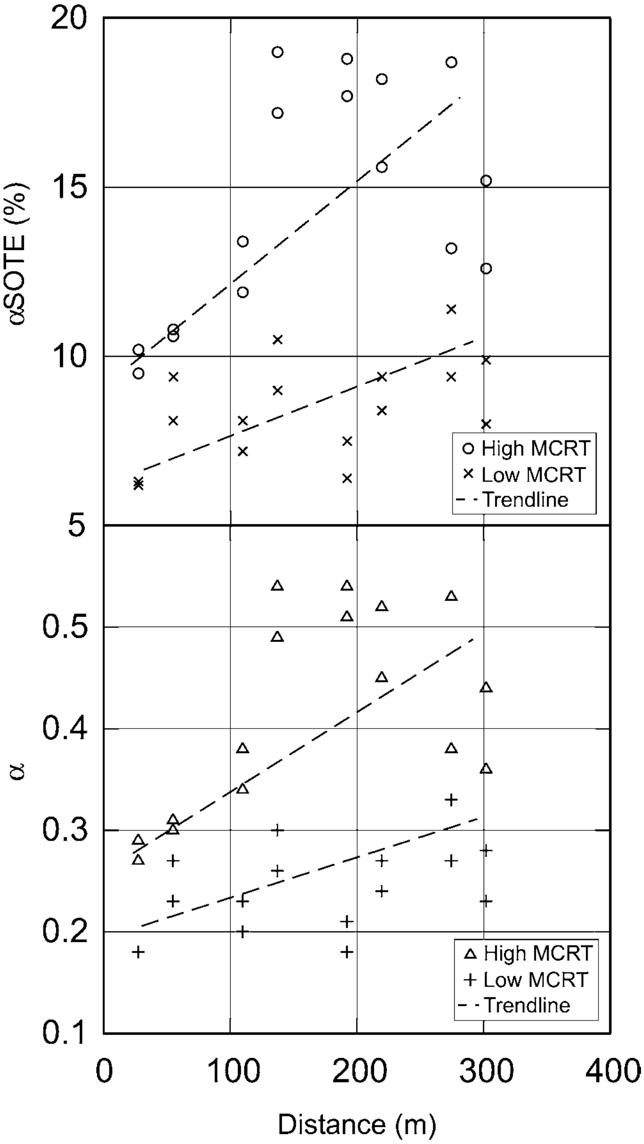

Figure 2—Efficiency parameters versus tank length for two equally designed tanks operating at different MCRTs.

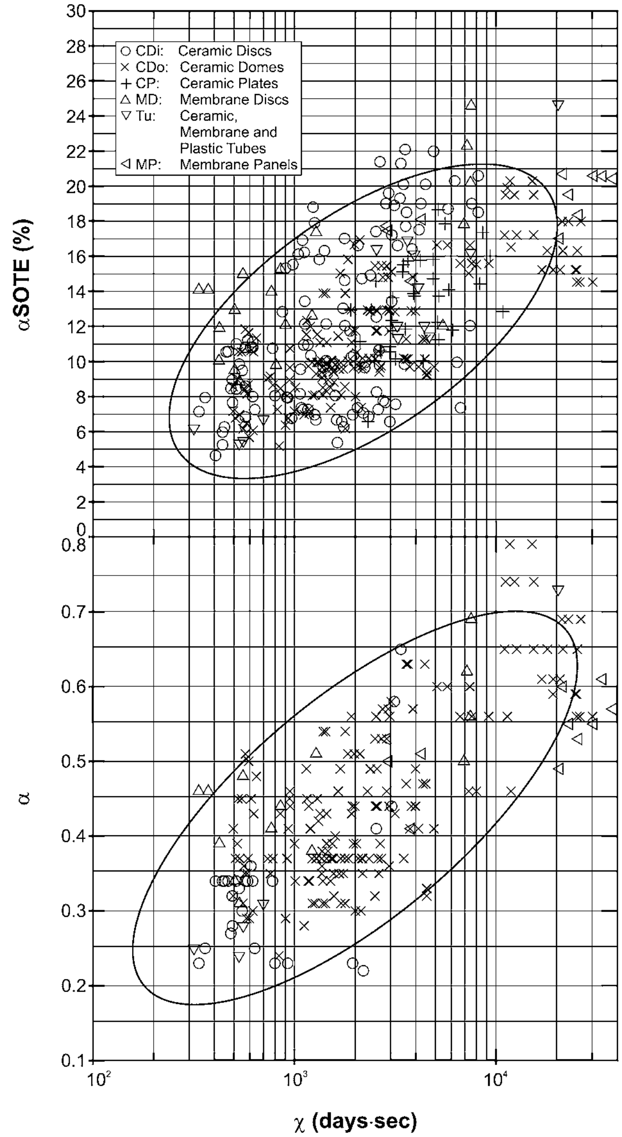

Figure 3—Measured efficiency parameters versus plant characteristic number χ. The ellipses represent 90% confidence, with standard deviations values given by the vertical extremes of the ellipse at a given χ value.

Equation 1 was used to normalize the air flux, as follows:

$$Q_N = \frac{AFR}{a \cdot N_D \cdot Z} \quad (1)$$

Where

AFR = airflow rate, m^3/s,
a = diffuser specific area, m^2,
N_D = total diffuser number, and
Z = diffuser submergence in meters.

In this fashion, the normalized air flux, Q_N, could be compared between different plants, and showed to vary from 3.601×10^{-04} to 2.186×10^{-02} s^{-1}.

Diffusers time-in-operation, cleaning method and frequency, and other process conditions were assembled from test reports and plant records. Unfortunately, there were too many missing or inconsistent data to allow statistical analysis. In some cases, high or low observations can be explained by site-specific knowledge, such as the ceramic domes or membrane discs discussed earlier. It is well known that periodic cleaning is needed to maintain fine-pore diffuser performance (U.S. EPA, 1985), but unfortunately our data cannot be used to verify these earlier observations.

Observations and Applications

Data Analysis. Data were plotted and analyzed with SYSTAT 9 (SPSS Corporation, Chicago, Illinois, 1999). To better confine the scatter, all operative parameters were grouped in the plant characteristic number χ, which has units of [T^2]:

$$\chi = \frac{MCRT}{Q_N} \quad (2)$$

Figure 3 shows efficiency parameters versus the plant characteristic group, χ, for all collected points. The ellipses in Figure 3 are

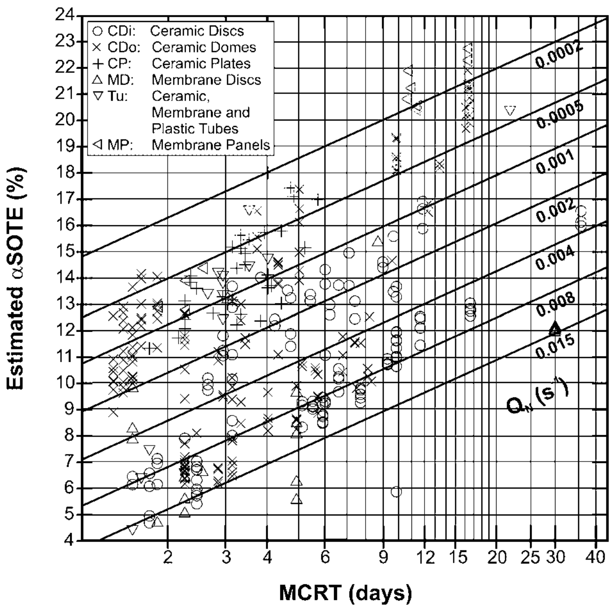

Figure 4—αSOTE vs. MCRT; Q_N is expressed as contours, calculated with eq 3. CDi: ceramic discs; CDo: ceramic domes; CP: ceramic plates; MD: membrane discs; PD: plastic discs; Tu: ceramic, plastic, and membrane tubes; and MP: membrane panels.

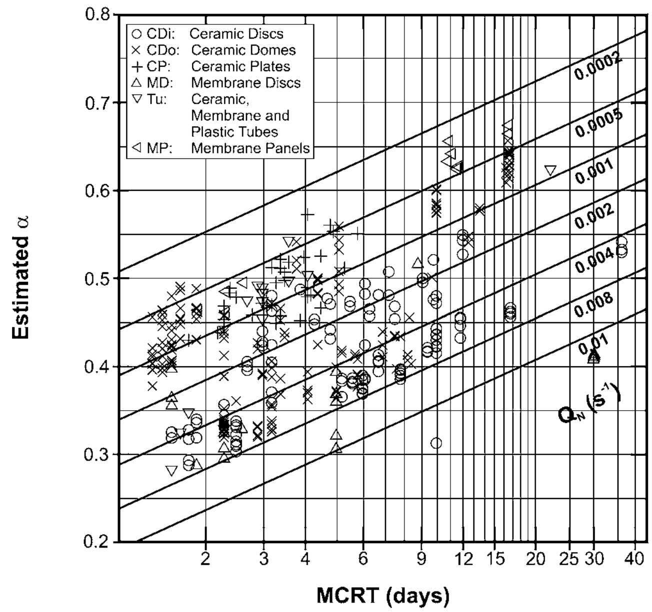

Figure 5—α vs. MCRT; Q_N is expressed as contours, calculated with eq 4. CDi: ceramic discs; CDo: ceramic domes; CP: ceramic plates; MD: membrane discs; PD: plastic discs; Tu: ceramic, plastic, and membrane tubes; MP: membrane panels.

centered on the sample means of α, αSOTE, and χ; unbiased sample standard deviations of efficiencies and χ determine their major axes, and the sample covariance between α, αSOTE and χ determine their orientation. In other terms, they represent 90% confidence, with standard deviation values given by the vertical extremes of the ellipse at a given χ value. Regression analyses were performed to estimate both α and αSOTE as linear functions of logχ. Results are as follows:

$$\alpha SOTE = 5.717\cdot \log \chi - 6.815 \quad (3)$$

$$\alpha = 0.172\cdot \log \chi - 0.131 \quad (4)$$

The $R^2$of eq 3 is 0.374, and the R^2 of eq 4 is 0.521. Regressions are highly significant, with the P parameters less than 0.001, and residuals are unbiased. The age of diffusers, maintenance history, and other site-specific conditions account for the rest of the variability. Figures 4 and 5 show data with eqs 3 and 4 plotted as contours.

Figure 4 shows the αSOTE as a function of MCRT, with contours showing αSOTE (eq 3) for equal, normalized air fluxes. Transfer efficiency is much higher at higher MCRTs and lower air fluxes, as expected. Data are presented for ceramic discs (CDi); ceramic domes (CDo); ceramic plates (CP); membrane discs (MD); plastic discs (PD); ceramic, plastic, and membrane tubes (Tu); and membrane panels (MP). There are many more observations for ceramic diffusers because they were developed earlier. Note that the effect of diffuser submergence is included in eq 1, and αSOTE does not need to be expressed per unit of depth. Figure 5 shows the α factor in a fashion similar to Figure 4. Figures 4 and 5 are useful because they illustrate the effect of the two key parameters on transfer rate. By following a contour line on Figure 4 or 5, the effect of MCRT on transfer rate is shown. By moving in the vertical direction from one contour to another, the overall effect of specific air flux is observed.

Application. To apply these results to treatment plant design or expansion, two hypothetical examples are proposed. First, as a design example, an algorithm can be implemented as shown in Figure 6. For a fixed wastewater load with a selected MCRT, the oxygen demand is first calculated as an OTR (mass O_2/unit time) and aeration tank size and side water depth are determined. Next, the diffuser type and the number of diffusers are selected, and an estimated αSOTE is assumed. The αSOTE can be selected based on manufacturers' information and literature values of α, or any other information available. The required airflow rate can now be calculated from the oxygen uptake rate and oxygen transfer efficiency, which allows the specific air flux to be calculated. Next, the design point is found on Figure 7 by locating the MCRT on the horizontal axis, and the contour that corresponds to the specific air flux. A new value of αSOTE is determined by reading the ordinate of the design point. If the new αSOTE is different than the assumed αSOTE by more than a small difference (e.g., 0.5%), a new airflow rate and specific air flux must be calculated using the new αSOTE to create a new design point. The new design point is located on Figure 7, and a third value of αSOTE is determined and compared to the second αSOTE. The process is repeated until the new αSOTE and previous αSOTE are approximately equal.

A numerical example is provided. Given an influent flowrate of 0.875 m^3/s (20 MGD), with a load of 180 mg/L MLSS, and assuming an yield of 0.5 and a decay coefficient of 0.06 $days^{-1}$, the required OTR will be 9540 kgO_2/day. Considering a hydraulic retention time of 4 hours, 3 tanks with dimensions 90 × 9 × 5 m (length × width × depth) each, and an initial αSOTE of 13.5%, the airflow rate will be 0.985 m^3/s. Considering for design 9" ceramic discs (a = 0.0373 m^2/diffuser) operating at $7.87\cdot 10^{-4}$ m^3/s per diffuser (1.5 standard cubic feet per minute per diffuser [SCFM/diff]), 1252 diffusers per tank are required. Given these data, it is possible to calculate $Q_N = 0.004152\ s^{-1}$. This value, together with

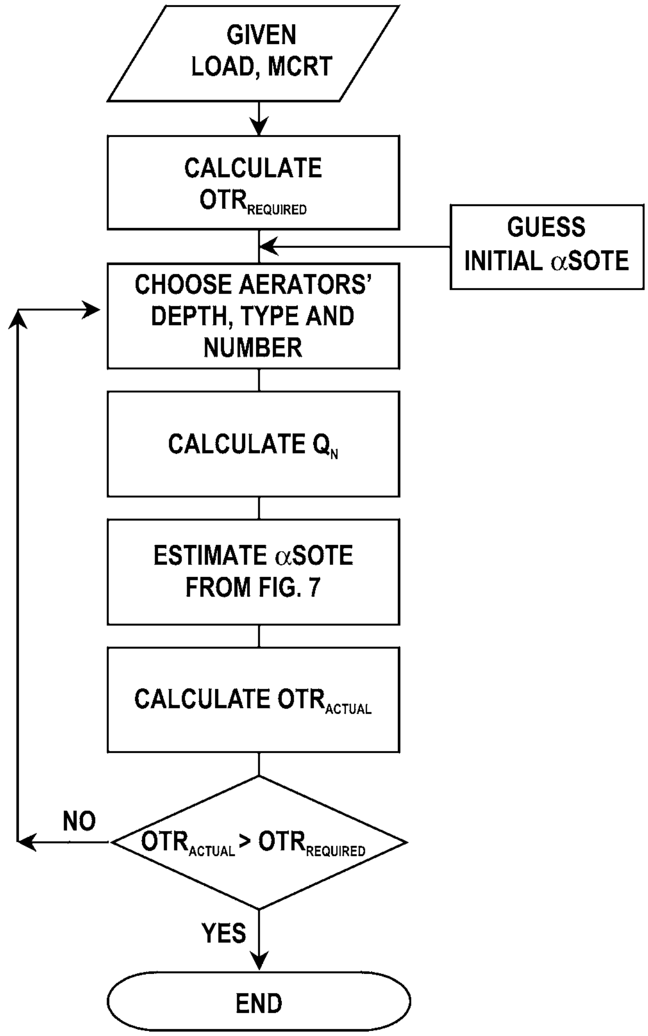

Figure 6—Aeration tank design flowchart.

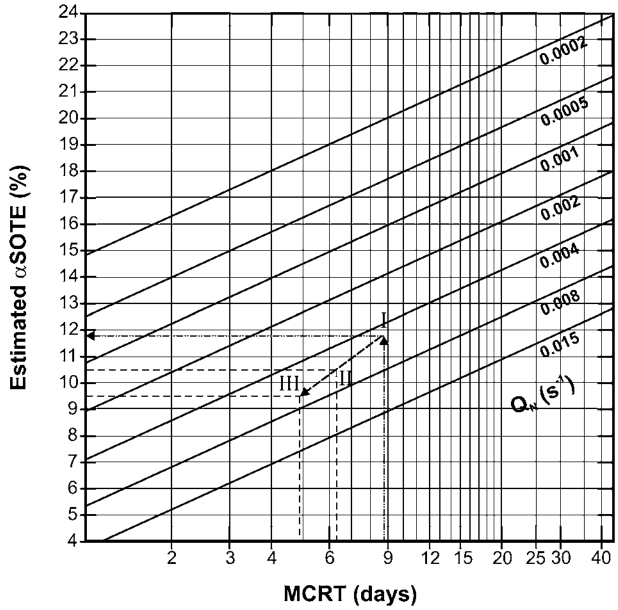

Figure 7—Design and verification graph. I: Flow = 0.875 m^3/s (20 MGD) (design example), Q_N = 0.0046 s^{-1}, MCRT = 8.7 days, $\alpha SOTE_{EST.}$ = 11.9 %; II: Flow = 1.094 m^3/s (25 MGD), Q_N = 0.0058 s^{-1}, MCRT = 6.3 days, $\alpha SOTE_{EST.}$ = 10.5 %; III: Flow = 1.313 m^3/s (30 MGD), Q_N = 0.0069 s^{-1}, MCRT = 4.9 days, $\alpha SOTE_{EST.}$ = 9.5 %.

the MCRT value of 8.7 days, is located on Figure 7 (point I). The new αSOTE is 11.9%. A new Q_N is calculated as 0.0051 s^{-1}, and the process converges at 11.7% after one iteration.

A second example is useful to illustrate growth in load on an existing plant and is shown in Figure 8. The additional load entering the plant will increase oxygen demand, and, to supply a higher oxygen mass, the aerators are operated at a higher airflow rate. This causes an increase in Q_N because the number of diffusers and tank geometry do not change. If the MLSS is not increased, the plant will operate at lower MCRT. This will cause two sources of reduced aeration efficiency: lower MCRT and higher airflow rate. Two scenarios are presented in Figure 7: design point I shows the initial design and is the same as the previous example; design point II shows a load increase from 0.875 to 1.094 m^3/s (20 to 25 MGD), with a drop in αSOTE from 11.9 to 10.5%. The increase from 1.094 to 1.313 m^3/s (25 to 30 MGD) to design point III results in additional drop in efficiency to 9.5%. The practical effect of the load increase will be an increase in electric power consumption per unit of load treated. The importance of the increased load example is to understand that there are two reasons for reduced aeration efficiency: increased airflow rate and reduced MCRT.

Additional Observations. There exists some question over the effect of anoxic selectors on oxygen transfer rates. The removal of soluble substrate in a denitrifying or anaerobic selector might improve alpha factors. Fisher and Boyle (1999) found no improvement, but note that their experimental conditions might have prevented them from noticing an improvement. Their test plants showed high transfer efficiencies before the addition of selectors because of high MCRTs, which may have precluded observation of even higher transfer efficiencies after adding the selector. Mueller et al. (2000), in comparing a conventional activated sludge process with a contact stabilization process using a selector, found a modest 10 to 15% improvement in alpha factor. Only three of our plants (Plants B, J, S in Table 1) had denitrifying selectors and were operating at high MCRT with high transfer efficiency. Therefore, increased transfer efficiency cannot be related to the selector, and our situation is similar to Fisher and Boyle (1999). To answer this question, a series of new tests will need to be performed. The importance of this information will increase because more and more plants are being required to remove nitrogen.

The observations presented in this paper are limited to the activated sludge process. Recently, evidence exists that membrane bioreactors (MBRs), which operate at high MLSS concentrations, have suppressed α factors, and that the α factor is inversely proportional to MLSS (Cornel et al., 2002). There is no evidence of a correlation between α factor and MLSS in our data sets. We believe that mass transfer interactions in MBRs are fundamentally different, and that correlations between oxygen transfer rates or α factors and MLSS or MCRT for activated sludge plants should not be extrapolated to MBRs, or vice versa.

Conclusions

The conclusions presented in this study are that MCRT and normalized air flux, Q_N, are major determining factors for process water oxygen transfer efficiency. These observations have been

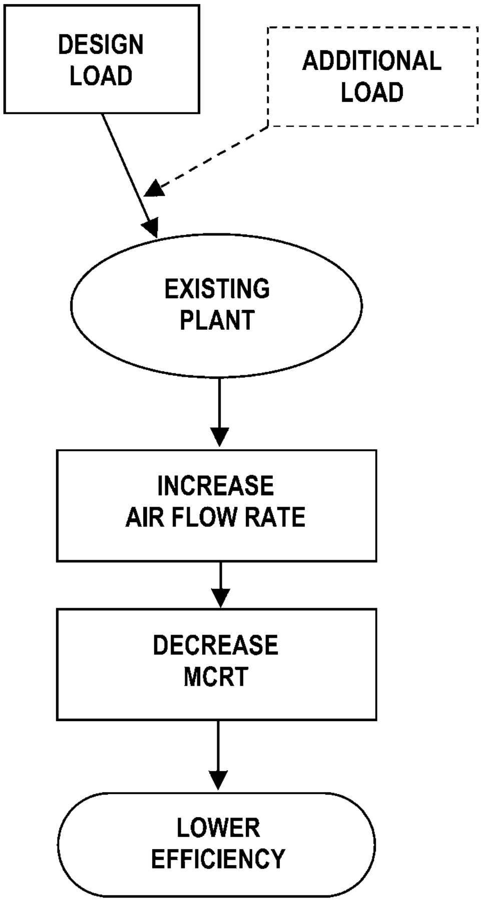

Figure 8—Aeration tank verification flow chart.

made previously, but they have not been supported with such a large dataset. Also, taking the ratio between MCRT and Q_N allows one to directly assess plant performance. The data do not support differences in transfer efficiencies or α factors for different types of fine pore diffusers.

A second conclusion relates to the relationship between MCRT and overall aeration costs. Air requirements increase with increasing MCRT, especially if nitrification occurs. Increased aeration efficiency will partially compensate for the increased air requirements, suggesting that operation at higher MCRTs may not be as expensive as heretofore believed (Stenstrom and Andrews, 1980).

Further work is in progress to determine additional relationships such as diffuser age and cleaning programs.

Acknowledgments

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References

Allbaugh, T. A.; Kang, S. J. (1989) Fine Pore Diffuser Case History for Frankenmuth, Michigan, EPA/600/R-94/100; U.S. Environmental Protection Agency: Washington, D.C.

ASCE (1984, 1991) Measurement of Oxygen Transfer in Clean Water, ASCE 2-91; American Society of Civil Engineers: New York.

ASCE (1997) Standard Guidelines for In-Process Oxygen Transfer Testing, ASCE 18-96; American Society of Civil Engineers: New York.

Boyle, W. C.; Craven, A.; Danley, W.; Rieth, M. (1989) Oxygen Transfer Studies at the Madison Metropolitan Sewerage District Facilities, EPA/600/R-94/096; U.S. Environmental Protection Agency: Washington, D.C.

Cornel, P.; Wagner, M.; Krause, S, (2002) Investigation of Oxygen Transfer Rates in Full Scale Membrane Bioreactors, Paper Reference No. e21291a; Darmstadt Technical University: Darmstadt, Germany.

Fisher, M. J.; Boyle, W. C. (1999) Effect of Anaerobic and Aerobic Selectors on Oxygen Transfer in Water. *Water Environ. Res.,* **71** (1), 84–93.

Gilbert, R. G.; Sullivan, R. C. (1989) Off-Gas Analysis Results and Fine Pore Retrofit Case History for Hartford, Connecticut, EPA/600/R-94/105; U.S. Environmental Protection Agency: Washington, D.C.

Hsieh, C. C.; Ro. K. S.; Stenstrom, M. K. (1993a) Estimating Emissions of Twenty VOCs: Surface Aeration. *J.—Environ. Eng. Div.,* **119,** 1077–1098; American Society of Civil Engineers: New York.

Hsieh, C. C.; Babcock, R. W.; Stenstrom, M. K. (1993b) Estimating Emissions of Twenty VOCs: Diffused Aeration, *J.—Environ. Eng. Div.,* **119,** 1099–1118; American Society of Civil Engineers: New York.

Iranpour, R.; Magallanes, A.; Zermeno, M.; Moghaddam, O.; Wilson, J.; Stenstrom, M. K. (2000a) Assessment of Aeration System Performance Efficiency: Frequent Sampling for Damage Detection, *Water Environ. Res.,* **72** (3), 363–376.

Iranpour, R.; Magallanes, A.; Zermeno, M.; Varsh, V.; Abrishamci, A.; Stenstrom, M. K. (2000b) Assessment of Aeration Basin Performance: Sampling Methods and Tank Coverage, *Water Res.,* **34** (12), 3137–3152.

Iranpour, R.; Stenstrom, M. K. (2001) Relationship Between Oxygen Transfer Rate and Airflow for Fine-Pore Aeration under Process Conditions. *Water Environ. Res.,* **73** (3), 266–275.

Iranpour, R.; Shao, Y. J.; Ahring, B. K.; Stenstrom, M. K. (2002) Case Study of Aeration Performance under Changing Process Conditions. *J.—Environ. Eng.,* **128,** 562–569; American Society of Civil Engineers: New York.

Kessner, H. J.; Ribbius, F. J. (1935) Practical Activated Sludge Research. *J. Proc. Inst. Sew. Purification*, 50–56.

Marx, J. J. (1989) Fine Pore Diffuser System Evaluation for the Green Bay Metropolitan Sewerage District, EPA/600/R-94/093; U.S. Environmental Protection Agency: Washington, D.C.

Masutani, G.; Stenstrom, M. K. (1990) Fine Pore Diffuser Fouling: The Los Angeles Studies, UCLA ENG 90-02, January, 1–145; University of California: Los Angeles, California.

Mueller, J. A.; Saurer, P. D. (1989) Case History of Fine Pore Diffuser Retrofit at Ridgewood, New Jersey, EPA/600/R-94/098; U.S. Environmental Protection Agency: Washington, D.C.

Mueller, J. A.; Kim, Y. K.; Krupa, J. J.; Shkreli, F.; Nasr, S.; Fitzpatrick, B. (2000) Full-Scale Demonstration of Improvement in Aeration Efficiency.

J.—Environ. Eng., **126** (6), 549–555; American Society of Civil Engineers: New York.

Redmon, D. T.; Boyle, W. C.; Ewing, L. (1983) Oxygen Transfer Efficiency Measurements in Mixed Liquor Using Off-Gas Techniques. *J.—Water Pollut. Control Fed.,* **55,** 1338–1347.

Sedory, P. E.; Stenstrom, M. K. (1995) A Dynamic Model for the Prediction of Aeration Basin Temperature. *J.—Environ. Eng. Div.,* **121** (9), 609–618.

Stenstrom, M. K.; Andrews, J. F. (1980) Cost Interactions in an Activated Sludge System. *J.—Environ. Eng. Div.,* **106** (EE4), 787–796; American Society of Civil Engineers: New York.

Stenstrom, M. K.; Gilbert. R. G. (1981) Effects of Alpha, Beta and Theta Factors in Design, Specification and Operations of Aeration Systems. *Water Res.,* **15,** 643–654.

Talati, S. N.; Stenstrom, M. K. (1990) Aeration Basin Heat Loss. *J.—Environ. Eng. Div.,* **116,** 70–86; American Society of Civil Engineers: New York.

U.S. EPA (1985) Fine Pore (Fine Bubble) Aeration Systems, EPA/625/8-85/010; U.S. Environmental Protection Agency: Cincinnati, Ohio.

U.S. EPA (1989) Fine Pore (Fine Bubble) Aeration Systems, EPA/625/1-89/023; U.S. Environmental Protection Agency: Cincinnati, Ohio.

Warriner, R. (1989a) Oxygen Transfer Efficiency Surveys at the Jones Island Treatment Plants, 1985–1988, EPA/600/R-94/094; U.S. Environmental Protection Agency: Washington, D.C.

Warriner, R. (1989b) Oxygen Transfer Efficiency Surveys at the South Shore Wastewater Treatment Plant, 1985–1987, EPA/600/R-94/099; U.S. Environmental Protection Agency: Washington, D.C.