Arnold Schwarzenegger
Governor

A DIGITAL CONTROL SYSTEM FOR OPTIMAL OXYGEN TRANSFER EFFICIENCY

APPENDIX F: TECHNICAL PAPERS

PIER FINAL PROJECT REPORT

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Public Interest Energy Research Program

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Appendix F

Technical Papers

The dissemination of the research results from this project resulted in a number of publications and technical papers that were presented at water and wastewater symposiums. Examples of these include the following:

- 25th West Coast Emergency Management Congress Conference
- IWA (International Water Association) Leading-Edge Conference on Water and Wastewater Technologies
- IWA 4th Specialist Conference on Efficient Use and Management of Urban Water Supply
- Summary Report of OTE Study to Wastewater Industry and Member Electric Utilities

Below are the papers resulting from this project:

- *Aeration of large-scale municipal wastewater treatment plants: state of the art,*
  Diego Rosso, Lory E. Larson, Michael K. Stenstrom

- *Aeration Efficiency Monitoring with Real-Time Off-Gas Analysis,*
  Diego Rosso, Shao-Yuan Leu, Pan Jiang, Lory E. Larson, Roger Sung, Michael K. Stenstrom

- *Real-Time Transfer Efficiency Monitoring for Wastewater Aeration Systems,*
  Shao-Yuan Leu, Diego Rosso, Pan Jiang, Lory E. Larson, Michael K. Stenstrom

- *Documenting Improved Aeration Efficiency Using Off-Gas Analyses,*
  Shao-Yuan Leu, Pan Jiang, Diego Rosso, Lory E. Larson, Roger Sung, Pramod Kulkarni, Michael K. Stenstrom

Finally, a presentation was made to CWEA in Ontario California in April 2007. The abstract for the presentation is included below along with the PowerPoint presentation.

- *Documenting Improved Aeration Efficiency Using Off-Gas Analyses,*
  Shao-Yuan Leu, Pan Jiang, Diego Rosso, Lory E. Larson, Roger Sung, Pramod Kulkarni, Michael K. Stenstrom

Aeration of large-scale municipal wastewater treatment plants: state of the art

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Abstract – Aeration is the most energy-intensive operation in wastewater treatment, amounting to 45-75% of plant energy costs. Fine-pore diffusers are today almost ubiquitous in municipal wastewater aeration, due to their advantageous aeration efficiency (mass of oxygen transferred per unit energy required). Nevertheless, older municipal treatment facilities and many industrial treatment plants are still equipped with coarse-bubble or surface aerators. Fine-pore diffusers are subject to two major disadvantages: a) fouling, if not cleaned periodically; b) decrease in oxygen transfer efficiency caused by dissolved surfactants. Coarse-bubble and surface aerators are typically not subject to the traditional problems affecting fine-pore diffusers. Nonetheless, they achieve oxygen transfer at the expense of increased energy intensity. The increased biomass concentration associated with high mean cell retention time (MCRT) operations has a beneficial effect on aeration. Nutrient-removing selectors are able to further increase aeration efficiency, as they sorb and utilize the readily available substrate which otherwise would accumulate at bubble surfaces and dramatically decrease aeration efficiency. We summarise here our 30-year long experience in aeration research, and results obtained with clean- and process-water tests are used to show the beneficial effects of high MCRT operations, the beneficial effect of selectors, and the decline of aeration efficiency due to dissolved surfactants.

Keywords – Activated Sludge, Aeration, Alpha, Efficiency, Oxygen Transfer, Wastewater

Introduction

Aeration systems

Aeration is an essential process in the majority of wastewater treatment plants and accounts for the largest fraction of plant energy costs, ranging from 45 to 75 % of the plant energy expenditure (Reardon, 1995). Aeration systems transfer oxygen into the liquid media by either shearing the liquid surface with a mixer or turbine, or by releasing air through macroscopic orifices or porous materials. Falling droplets and rising coarse bubbles have large interfacial gas-liquid velocity gradients and can be grouped as high flow regime interfaces, whereas fine bubbles have low interfacial velocity gradients and can be grouped as low flow regime interfaces (Rosso and Stenstrom, 2006a).
Fine pore diffusers (which produce fine-bubbles) have become the most common aeration technology in wastewater treatment in developed countries, due to their higher efficiencies on the basis of energy consumption (Stenstrom et al., 1984). 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 produce 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, also creates fine bubbles, but does so without using small

orifices. Fine bubbles from turbines or jets should be grouped with high flow regime interfaces, since mechanical energy is used to shear large bubbles into fine bubbles.

The impact of cell retention time

The most important process parameter to affect aeration efficiency is the mean cell retention time (MCRT). MCRT is directly related to the biomass concentration, and dictates oxygen requirements. Aeration efficiency and alpha factors (ratio of process-water to clean-water mass transfer) are higher at higher MCRTs. Biological nutrient removal processes, by operating at increased MCRTs, have improved aeration efficiency. Furthermore, anoxic and anaerobic selectors in nutrient removal plants have beneficial effects that go beyond nutrient removal or improved settling characteristics. By utilising the readily available carbon in the wastewater, they remove the faster acting surfactants, which have the most dramatic impact in reducing oxygen transfer.

Literature studies (US EPA, 1989, Rosso et al., 2005) showed that the oxygen transfer efficiency is directly proportional to MCRT, inversely proportional to air flow rate per diffuser, and directly proportional to geometry parameters (diffuser submergence, number and surface area of diffusers). The MCRT determines the net oxygen requirement and relates to the degree of treatment and removal of oxygen transfer reducing contaminants, such as surfactants. Higher MCRT systems remove or sorb the surfactants early in the process, which improves average oxygen transfer efficiency. The net effect of increasing MCRT is to increase the oxygen requirements, improve removal of biodegradable organics (Khan *et al.*, 1998), and improve the overall oxygen transfer efficiency. The increase in oxygen requirement is partially or more than offset by the savings produced by the higher transfer efficiency.

The air flow rate influences the fluid dynamics of bubbles: the higher the air flow rate per diffuser or orifice, 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 at greater submergence and tank coverages (ratio between diffusing area and total tank area) the mass transfer time and surface area are greater.

Role of selectors

Almost all new activated sludge process designs utilize selectors, either anoxic or anaerobic. An indirect benefit of selectors is improved oxygen transfer efficiency (Fisher and Boyle, 1999), and is in addition to the well known oxygen credit provided by anoxic removal of influent substrate and reduction in filamentous organisms (Harper and Jenkins, 2003). There is growing evidence that processes operating at higher MCRT are more efficient in removing anthropogenic compounds, such as pharmaceuticals (Soliman *et al.*, 2004).

For these and other reasons, anoxic selectors for nitrification/denitrification (NDN) should always be evaluated as an alternative to conventional treatment. Our previous analysis showed that NDN operation can have lower total operating cost (aeration + sludge disposal costs - methane credit) than a nitrifying-only or a conventional treatment plant (Rosso and Stenstrom, 2005). If conventional process operating cost was normalized to 1.00, nitrifying-only will have a total cost of 1.13, and NDN operations will have a total cost of 0.88. NDN operation offers an oxygen credit due to its process nature, and higher oxygen transfer efficiencies associated with the higher MCRT. The two factors overcome the additional oxygen demand that produced by the longer MCRT.

Diffuser fouling, scaling, and cleaning

Different methods have been used to clean fine-pore diffusers and vary in complexity and cost. The simplest method is to dewater the aeration tank and wash the diffusers from the tank top. This form of cleaning, called tank top hosing, is effective in removing biological slime accumulation, and generally restores or partially restores efficiency. For cases where inorganic precipitates (silica, calcium carbonate, gypsum, etc.) have caused scaling, acid cleaning may be required. Manually washing with low-strength hydrochloric acid (10 to 15% wt) is popular and acid gas cleaning using hydrochloric acid gas or acetic acid injected to air distribution lines is also possible (Schmit et al., 1989).

The oxygen transfer efficiency of fine-pore diffusers inevitably decreases over time. At the same time, back pressure (often called dynamic wet pressure or DWP) usually increases, and in some cases dramatically. This DWP increase is due to clogging of pores in ceramic diffusers (USEPA, 1989), or is associated with a permanent change in orifice characteristics for polymeric membranes (Kaliman *et al*., 2007). Both effects account for the decrease in overall process efficiency and power wastage. Cleaning fine-pore diffusers is almost always required and restores process efficiency and reduces power costs. Observations of 94 field tests show that efficiency decreases with time and the greatest rate of decrease occurs in the first 24 months of operation (Rosso and Stenstrom, 2006b). Efficiency decline was quantified and included in cost analyses, and the net-present worth was compared to cleaning costs. The cleaning frequency is always higher for higher fouling rates and optimal frequency was as short as 9 months and never more than 24 months.

Background

Clean water tests

Clean water testing (ASCE 2007) can be performed to compare different equipment and configurations. The results are reported as Standard Oxygen Transfer Efficiency (SOTE, %), Standard Oxygen Transfer Rate (SOTR, kgO2/ hr), or Standard Aeration Efficiency (SAE, kgO2/kW-hr). Care must be exercised in using SAE, since different power measurements can be made. Generally “wire” power is usually preferable, which includes blower, coupling, gearbox and motor inefficiencies. Standard conditions are well defined, and correspond to 20^{o}C, zero DO, mean atmospheric pressure, and zero impact of water salinity or other contaminants (e.g., α factor = 1.0, β factor = 1.0). Clean water test results can be used as warranty to verify performance and can also create a competitive bidding environment among manufacturers.

Process water tests

For process water conditions, results are reported as OTE, OTR and AE, which include the impacts of non-standard conditions. For off-gas results, it is convenient to use αSOTE, or αSOTR; these two parameters are corrected for all non-standard conditions except the α factor. This is possible because the other non-standard conditions are easily measured and corrected. The α factor, which is a ratio of mass transfer coefficients in process to clean water, can be calculated from off-gas results if clean water data are available. In fouled aeration systems, a second parameter, F, is used to define the degree of fouling. Therefore the efficiency of a new fine pore aeration system could be defined by αSOTE and a used or fouled system by αFSOTE. In this paper, αSOTE or αFSOTE is used for process water transfer efficiencies. To compare the results presented here to actual process conditions, the other corrections, such as DO concentration and temperature must be applied.

In order to better define aerator performance, off-gas testing has been extensively used to measure diffused aeration efficiency. Off-gas testing was developed by Redmon et al. (1983) in conjunction with the US EPA sponsored ASCE Oxygen Transfer Standards Committee. This committee produced a fine pore manual (US EPA, 1989), a clean water oxygen transfer standard (US EPA, 1984, 1991, 2007) and guidelines for process water testing (US EPA, 1997). Clean water testing and off-gas 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. These methods are now widely used in the United States (e.g., Redmon et al., 1983; Mueller and Stensel, 1990; Iranpour et al., 2002), Europe (e.g., Kayser, 1979; Frey, 1991; Libra et al., 2002; Wagner et al., 2003, Gillot et al., 2005). Off-gas analysis is also being proposed as an additional aeration control mechanism (Trillo et al., 2004). The results reported in this paper all conform to methods sanctioned by the ASCE standard and guidelines.

Results and discussion

Conventional treatment, typically performed at lower MCRT has lower biomass concentrations, and less chance for the dissolved substrate to be quickly sorbed by the biomass. Higher MCRT operations have the advantage of higher biomass concentration. Given the same average MCRT, treatment systems using anaerobic selectors or coupling nitrification and denitrification have the additional advantage of partial removal or sorption of readily biodegradable substrate (rbCOD) in the selector zone. This is beneficial because of the decreased overall oxygen requirements (in the case of anoxic or nitrate-reducing selectors), and the decreased rbCOD accumulation at bubble surfaces that severely reduces oxygen transfer (Eckenfelder and Ford, 1968; Rosso and Stenstrom, 2006a).

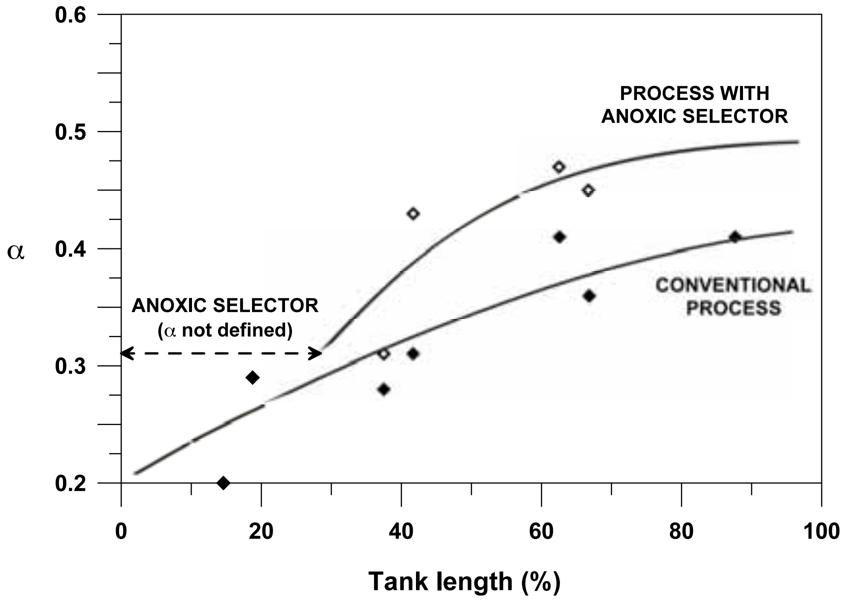

Figure 1. Effect of tank length and anoxic selectors on α.

Fig. 1 shows both effects. The first 30% of the aeration tank was under aerated and functioned as a *de facto* anaerobic selector. The α factors are low at the head of the aeration tank, depressing transfer rate, where unfortunately is location of greatest oxygen uptake rate.

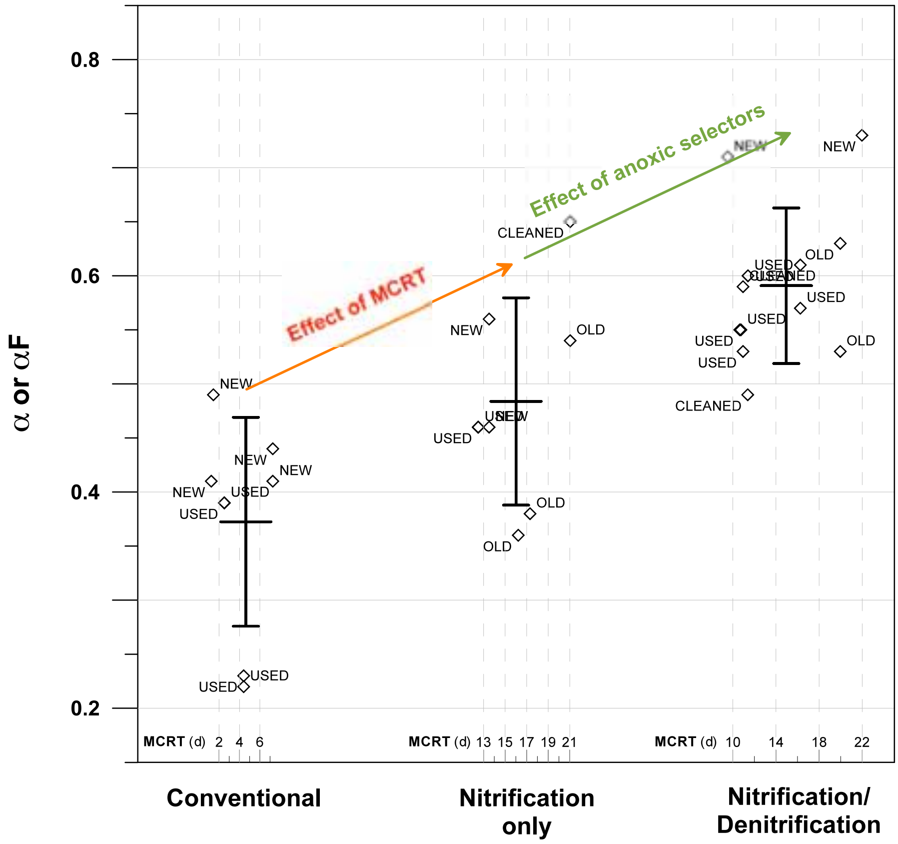

Figure 2.

Effect of mean cell retention time (MCRT), diffuser condition and selectors on α.

The tanks shown in Fig. 1 are from a low MCRT system and show a rapidly increasing alpha factor. In cases where the process is at high MCRT, the average alpha factor will be greater and if there is internal mixed liquor recirculation, the gradient is reduced. Internal recirculation is normally used to improve nitrogen removal, but also distributes load, reducing amount of aeration tapering that is required. Fig. 2 shows the results of 28 off-gas tests at plants that are low MCRT, carbon-only removal, nitrifying only and nitrifying-denitrifying (NDN, such as the MLE process). This figure also shows the effect MCRT and diffuser condition (new, used, old) on transfer rate. Increased MCRT is the major effect on transfer rate, with the average MCRT increasing from approximately 5 days for conventional to approximately 15 days for both nitrifying and NDN treatment plants. The average alpha factor increases from 0.37 to 0.48 to 0.59 for conventional, nitrifying and NDN systems, respectively. The change in alpha from nitrifying to NDN is the impact of rbCOD removal in the selectors. Also note the effect of diffuser condition. Points in the upper range for each process are tests of new or recently cleaned diffusers (i.e., α factors), while the lower numbers (i.e., αF factors) are used (< 24 months operation) and old (> 24 months).

The rbCOD is partially composed of surface active agents or surfactants, which are typically discharged as oils, soaps and detergents. The surfactants, because of their amphiphilic nature, accumulate at the air-water interface of rising bubbles. The surfactant accumulation increases the rigidity of the interface and reduces internal gas circulation and overall transfer rate (Rosso and Stenstrom, 2006a). The surfactant effect can be partially offset by increasing the flow regime (i.e., coarse bubbles). Fig. 3 shows alpha factor as a function of the bubbles' Reynolds (Re) number. At low (Re), an increase in (Re) decreases alpha. This occurs because the bubble is rising as a solid sphere. At higher (Re), the buoyancy and drag forces are sufficient to cause internal bubble circulation. At very high (Re), practically achievable only with coarse bubbles, surfactant effects are nearly offset, increasing alpha factor at the expense of energy efficiency or low SAE.

Fig 3 also shows the impact of two different surfactants, a “fast” with high diffusivity (sodium dodecyl sulphate, a.m.u ~ 10^2) and a “slow” with lower diffusivity (polyvinylpyrrolidone, a.m.u ~ 10^4) surfactant. The fast surfactant more dramatically suppresses the transfer rate because of its greater diffusion rate and greater accumulation at the bubble surface.

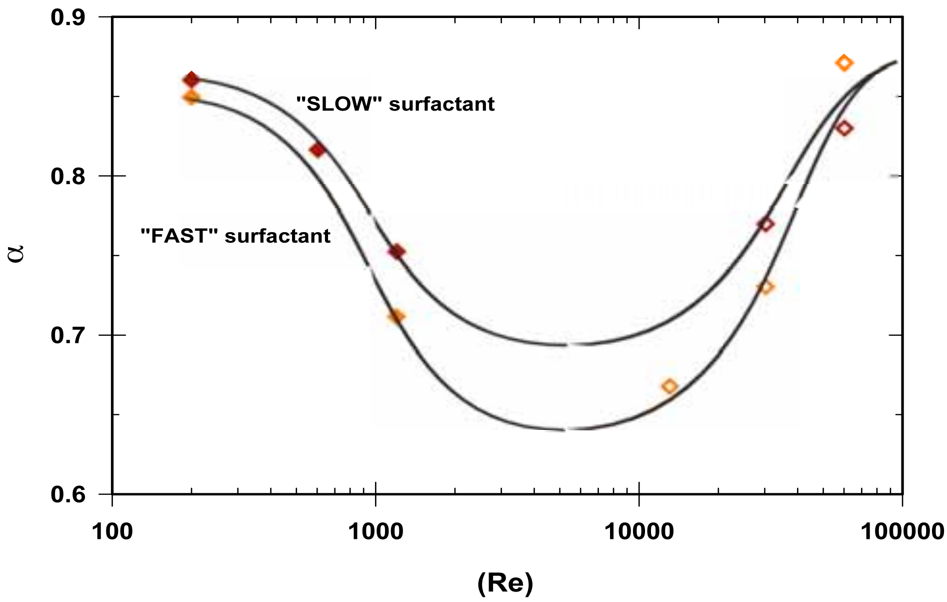

Figure 3. Effect of flow regime on alpha factors for fine- (low Re) and coarse- (high Re) bubbles in two different surfactant solutions.

Figure 4 shows this effect in process and clean water. The horizontal axis is air flow per diffuser. At low air flow, fine bubbles are created while at high flow coarse bubbles occur. In clean water high transfer efficiencies result, and are depressed to a greater degree (low alpha factor) at low air flow rate (i.e., the middle (Re) range of Fig. 3), while at high air flow rates (i.e., the upper range of (Re) in Fig. 3), less depression occurs. This explains why fine bubble diffusers have lower alpha factors. Note that even though the alpha factors are lower for fine bubble diffusers, they are still more energy efficient, with αFSAE of 1.38 kg_{O2}/kWh as opposed to 1.00 kg_{O2}/kWh αFSAE for coarse bubble diffusers. Also note that the data presented in Fig. 4 are for a low density fine pore diffuser system, and more recent high density systems have higher transfer rates.

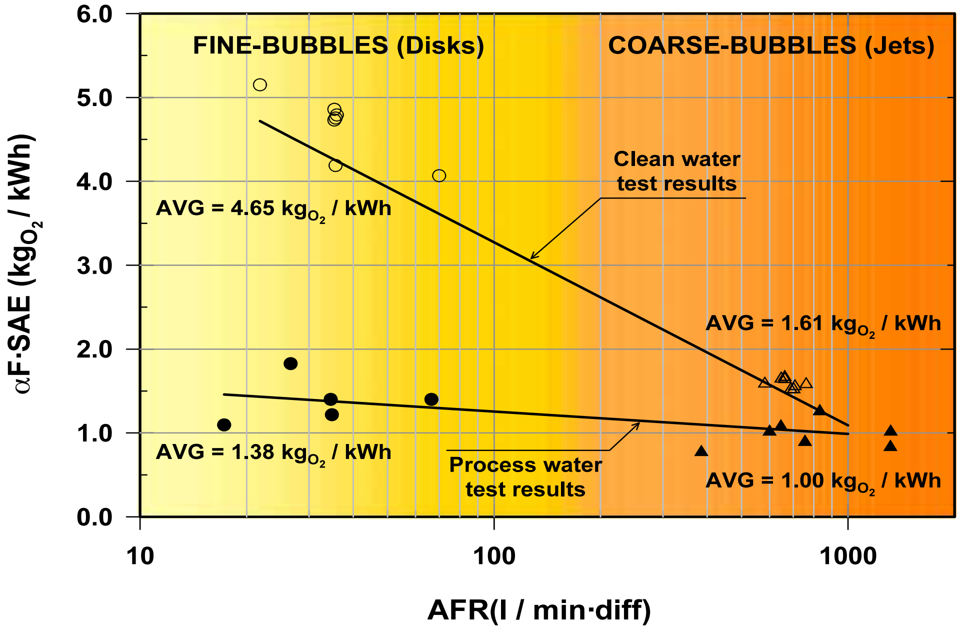

Figure 4. Variation in standard aeration efficiency for fine- and coarse-bubble diffusers in clean and process water (data from Yunt and Stenstrom, 1996).

Summary and conclusions

The required energy for aeration is the largest fraction of plant operating costs. Fine-pore diffusers have higher aeration efficiency, but their efficiency declines with bacterial fouling and with the presence of surfactants in the water. Coarse-bubbles and droplets can partially or completely offset these problems at the expense of energy efficiency ($mass_{O2}$ / energy).
In this paper we summarise our research over the past three decades. Clean- and process-water tests show the advantage of fine- versus coarse-bubble diffusers. When high transfer rates ($mass_{O2}$ / time) are required, coarse-bubbles may be the only solution, but have higher energy demand and operating costs. When the choice between fine- and coarse-bubble diffusers is permitted, fine-bubble diffusers have the advantage of higher transfer efficiency, lower energy requirements (lower operating costs), but require periodic cleaning.
Operations at high mean cell retention time have a beneficial effect on aeration efficiency and, when nutrient-removing selectors are employed, aeration efficiency is further increased. Whilst removing nutrients, selectors uptake readily available substrate, which otherwise accumulates on bubble surfaces and dramatically reduces aeration efficiency.

Acknowledgement

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Aeration Efficiency Monitoring with Real-Time Off-Gas Analysis

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Fine-pore diffusers replaced almost to completion coarse-bubble diffusers in municipal wastewater treatment plants, because of their increased efficiencies per unit energy consumed (Standard aeration efficiency or SAE, $kg_{O2} \cdot kWh^{-1}$). Inevitably, fine-pore diffusers experience fouling and/or scaling, depending on process conditions, water quality, diffuser type, and time in operation (U.S. EPA, 1989). As a result, fine-pore diffusers must be routinely cleaned to contain aeration efficiency losses. The inability for operators to document diffuser fouling and quantify efficiency losses with time in operation is an operational challenge. Cleaning frequency and method determine long-term efficiency and maintain benefits of using fine-pore aeration (Rosso and Stenstrom, 2006a).

A simplified, automated off-gas monitoring instrument, operating in real-time mode and self-calibrating, was used to measure oxygen transfer efficiency (OTE, %) for extended periods of operation in three facilities. The off-gas technique measures oxygen transfer by analyzing the oxygen content in the off-gas stream leaving the aeration tank (Redmon et al., 1983). The mass balance between oxygen fed (21% mole fraction) and off-gas stream returns the OTE.

Figure 1 shows the behaviour of OTE compared to the air flow rate (AFR) over the diurnal cycle, corroborating previous evidence that load (i.e., surfactants) depresses oxygen transfer and α factors (Rosso and Stenstrom, 2006b). This also shows that the off-gas reading (OTE) carries valuable information to regulate AFR to its minimum possible value, and to predict the influent load concentration (C-COD). Figure 2 shows the oxygen requirement (calculated by influent C-COD) and oxygen transferred (recorded from the off-gas analyzer) for the same period. The difference between the two values (shaded areas) represents the oxygen wastage, therefore the margin for improvement.

This paper shows OTE monitoring and diffuser cleaning as strategies for energy-conservation in municipal wastewater treatment plants. In addition, we present the results of real-time off-gas testing and their applications, illustrating the capability of our instrument for monitoring energy use and for aeration feedback control. Results will be reported in the full-length paper as dimensionless energy efficiency-loss curves over extended periods of time. These curves predict cleaning events and can be used to implement effective cleaning schedules with resulting significant energy savings.

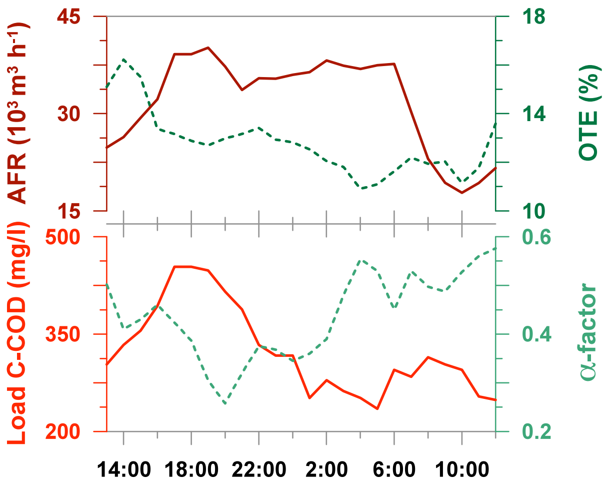

Figure 1. Oxygen transfer efficiency, air flow rate, load, and α factor during a 24-hr off-gas testing period.

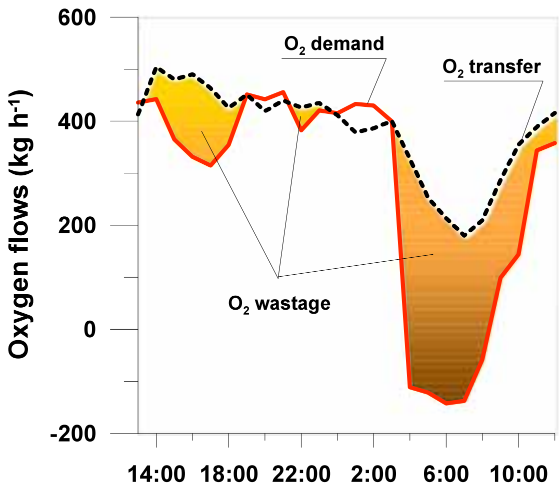

Figure 2. Rates of O_2 transfer and O_2 demand during the same cycle. Shaded areas represent O_2 wastage.

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Real-Time Transfer Efficiency Monitoring for Wastewater Aeration Systems

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Abstract - Aeration is the most energy intensive unit operation in municipal wastewater treatment. To improve oxygen transfer rates, fine-pore diffusers have been wildly applied in aeration practice. However, during operation, this type of diffusers suffers from fouling and scaling problems, which rapid decline in performance and significant increase in energy costs. Diffusers must be cleaned periodically to reduce energy costs. The cleaning frequency of diffusers is site-specific, and is shown by the reduction of oxygen transfer efficiency (OTE) with time in operation. Off-gas testing is the only technique that can measure real-time oxygen transfer efficiency. This paper presents time-series of off-gas testing measurements and their applications, which show the potential for full-scale implementation of energy-conservation practices. Our results include the real-time prediction of plant load and alpha factors from off-gas testing, as well as the quantification of the increased energy costs for aeration. Our off-gas analyzer is being used to develop an aeration efficiency monitoring protocol, and an aeration feedback control system for air blowing units.
Keywords – Efficiency, energy, activated sludge, off-gas, aeration, wastewater.

Introduction

Aerobic biological processes are the most common technology for municipal wastewater treatment. Their metabolism requires aeration, which is generally the most energy intensive operation in a wastewater treatment plant (Rosso and Stenstrom, 2005). In recent years, fine-pore diffusers have been widely used to reduce energy consumption, due to their advantageous oxygen transfer rates and aeration efficiency per unit energy required (e.g. standard aeration efficiency, or SAE, $kg_{O2}/kWh_{required}$).
Unfortunately, fine-pore diffusers suffer from fouling or scaling problems, and the lifetime of diffusers is hard to estimate. Diffusers made from both ceramic and polymeric membranes are susceptible to fouling and scaling. Fouled diffusers suffer a significant drop in oxygen transfer efficiency (OTE, %) and increase in dynamic wet pressure (DWP, i.e. the headloss for air release). If this situation is not corrected in time, greater air flow rates will be required, with increased energy and operating costs, which counter the benefits of fine-pore diffusers. Fouling scenarios are generally plant-specific, due to the different wastewater compositions and treatment operations. To optimize aeration systems performance and determine an appropriate cleaning frequency for diffuser fouling, real-time oxygen transfer monitoring is recommended (Rosso and Stenstrom, 2006a).
Several major strategies for estimating OTE have been developed, such as the clean water test (ASCE, 1993), process water tests (ASCE, 1997), and the off-gas test (Redmond et al., 1983). Amongst these methods, the off-gas test has the benefits of highest accuracy

and shortest response interval (ASCE, 1997). In this paper, we present results from our real-time off-gas analysis, which show the performance and economic improvement that real-time off-gas testing can bring to treatment plant operations. Two 24-hour experiments were performed in a full-scale treatment plant and the results confirm our previously published research, and that real-time off-gas testing can be used to predict the loads of influent oxygen demand. Our results suggest that real-time off-gas testing can produce appropriate feedback signals for blower control systems.

Background

Oxygen transfer for fine-pore diffusers can be characterized by several definitions, i.e. oxygen transfer rate (OTR, kg_{O2}/d), and oxygen transfer efficiency (OTE, %). In order to compare different aeration systems and different process and environmental conditions, OTR and OTE can be normalized to standard conditions (20℃, 0 mg/l of dissolved oxygen, 1 atm, 0 mg/l of salinity). Therefore, OTR can be standardised as SOTR, and OTE as SOTE (ASCE, 1993).

The current standard method to quantify SOTR and SOTE is the unsteady-state clean water test (ASCE, 1993). In process conditions, SOTE is lower than in clean water due to the effects of contamination, and conversion factors are required to quantify this reduction. The alpha factor (α) is the most commonly used conversion factor to quantify the effects of contaminants on oxygen transfer (ASCE, 1997):

$$\alpha = \frac{(k_L a)_{\text{process water}}}{(k_L a)_{\text{clean water}}} \qquad (1)$$

The process-water standardised oxygen transfer efficiency will therefore be the product of α and SOTE, or αSOTE (%). When clean water data are available, alpha-factors can be calculated as:

$$\alpha = \frac{\alpha SOTE}{SOTE} \qquad (2)$$

Former studies reported different α-factors for different aeration technologies (Kessener and Ribbius, 1935), operating conditions (Capela et al., 2004; Rosso et al., 2005), and the contaminants in wastewater (Wagner and Pöpel, 1996; Rosso and Stenstrom, 2006b).

The off-gas analysis measures the aeration performance without changing the operation of wastewater treatment and has the benefits of high accuracy and efficiency. Libra et al. (2002) applied the off-gas method to compare the performance of several different aeration devices. Krampe and Krauth (2003) used both unsteady-state clean water test and off-gas test to estimate the treatment efficiency of full-scale membrane bioreactors. Rosso et al. (2005) showed the correlation of oxygen transfer efficiency with diffuser air flux and mean cell retention time (MCRT), based on datasets from 372 off-gas measurements. Additionally, they confirmed the contamination effects of surfactants on the alpha factors complementing off-gas tests with dynamic surface tension measurements (Rosso et al., 2006). Furthermore, off-gas analysis has been shown as an appropriate analysis strategy to simulate the oxygen requirement and the bacteria activity of activated sludge process (Yuan et al., 1993).

In the off-gas analysis, the off-gas stream is collected from a hood floating onto the surface of the aeration basin, and treated to remove CO_2 and water vapour. As shown in Eq.3, the mass balance between oxygen fed ("IN", 21% mole fraction) and the off-gas stream ("OUT") is used to calculate the oxygen transferred as OTE:

$$OTE(\%)=\frac{p_{O_{2,IN}}-p_{O_{2,OUT}}}{p_{O_{2,IN}}} \qquad (3)$$

where p_i = partial pressure of oxygen in the gas streams.

By using this technique, OTE can be measured without information on air flow rate. Nevertheless, the off-gas analyzer can also measure the air flow rate passing through the instrument. By measuring the air flow rate for each single measurement, a weighted-average for the entire tank can be calculated (ASCE, 1997).

Methodology

Field experiments were performed in a full-scale treatment plant with the capacity of approximately 37800 m^3/day (10^7 gal/d or 10 MGD). The plant contains four process tanks (19 ft, or 5.8m in depth), each with four small anoxic sections and two aerobic sections. Before secondary treatment, an additional basin equalizes the flow from primary clarifiers, and recycle pumps return the process water from the end to the beginning of the process tanks. Following the processes tanks are two aerated polishing tanks (15ft, or 4.5m deep). The aerobic zones of the process and polishing tanks are equipped with fine-pore membrane type diffusers. Three off-gas hoods were positioned in the middle of the two aerobic sections and of the first section of the polishing tank.

We designed and built an automated version of the off-gas analyser originally developed by Redmon et al. (1983), and upgraded it to fit the needs of current aeration systems. Furthermore, we eliminated the need for crew of expert investigators to perform the off-gas testing, by making the instrument self-calibrating at each measurement. Therefore, our analyser was placed in full-scale municipal treatment plants, without need for expert supervision.

Two sets of experiments were performed. The first experiment tested the aeration performance of diffusers under normal operating conditions, and the second test was performed immediately after *in situ* liquid acid cleaning. Each of the off-gas tests was performed once per hour for the entire 24-hour cycle. The off-gas measurements included OTE, air flux, DO, and α-factor.

The results of the off-gas experiments were used to estimate energy costs for the aeration system before and after cleaning. For the cost calculations, assumptions were made as follows: blower energy requirement = 0.049 $kWh\cdot m^{-3}{}_{air}$ (0.033 $kW/ft^3\cdot min$); blower and motor efficiency = 61%; annual interest rate = 4%. The power requirements of blowers were calculated from the adiabatic compression function using airflow rate and blower pressure (Metcalf and Eddy, 2003). The calculation results were plugged into an economic analysis spreadsheet, after Rosso and Stenstrom (2006a), thus determining the optimum cleaning schedule for the treatment plant studied.

Results and Discussion

Figure 1(a) shows the behaviour of OTE compared to the air flow rate over a 24-hour cycle: when the air flow rate is at its maximum, OTE is at its minimum, and *vice versa*. The air flow rate is highest when the oxygen demand (i.e., the carbonaceous COD or C-COD) is highest, which is reflected in low OTE and low alpha values.

Alpha-factors calculated from αSOTE (measured with the off-gas technique) and manufacturer's clean water data (SOTE) are shown in Fig.1(b). Although OTE time-series were reported previously (Libra et al., 2002), this is the first report of time-series for alpha factors. The patterns of alpha and carbonaceous COD (C-COD) have analogous behaviour as OTE vs. air flow rate (AFR). This result shows that the off-gas reading (OTE) carries valuable information on AFR and load. For a given load, the off-gas signal can be used as a feedback control to regulate AFR to its minimum possible value, nonetheless achieving the same level of treatment, and to predict the influent load concentration.

Figure 2 shows the correlation between the alpha and air flux (air flow rate per unit of diffuser area, $m^3 \cdot s^{-1} \cdot m^{-2}$). The results were calculated from three different experiments: one clean water test and two process-water off-gas tests. In both off-gas tests, the results of a short term 24-hour measurements of αSOTE are negatively correlated with the air fluxes, which confirmed our previous long-term studies (Rosso et al., 2005). In addition, αSOTE is approximately half of the clean water SOTE (SOTE in labels on the graph). The process water αSOTE has different pattern for different time in operation: diffusers that have been in operation for a longer period without cleaning experience fouling, which is shown by a more rapid decline in performance with increasing air flux (labelled "before cleaning" in Fig.2).

Table 1 shows the aeration tank characteristics, the oxygen transfer data gathered from off-gas tests, and the energy consumptions calculated with our plant-cost algorithm. Our results suggest that the cleaning procedure improves oxygen transfer efficiency from 16.1% to 18.6%, thus reducing energy requirements to the same extent. Since the first test was performed 8 months before cleaning and the diffuser fouling had progressed after the off-gas test, the actual total saving is greater than the number measured. Hence, our calculated values represent the more conservative numbers.

The normalized power wasted in the tested aeration basin is shown in Figure 3. The power waste (bar plot) is defined as the power consumption exceeding the initial power requirement for new diffusers (Rosso and Stenstrom, 2006a). The total power requirements (solid line), increases after startup due to diffuser fouling. The diffuser cleaning frequency can be easily defined by comparing the cumulative wasted power costs and the site-specific cleaning costs.

Remarks on air blowing systems

Current control techniques for aeration systems are typically based on feedback signals provided by dissolved oxygen (DO) probes immersed in the aeration tanks. Dissolved oxygen concentration is an effect of oxygen transfer, and is an important indicator of proper process conditions. When the DO is too low, bacterial metabolism can be inhibited and the sludge composition may change, reducing the treatment efficiency or even causing process failures (i.e., sludge bulking). Conversely, high DO may pose problems for denitrification zones (which require anoxic conditions), and may represent excessive energy consumption (Ferrer, 1998; Serralta et. al., 2002). Many studies have focused on improvement of the DO control system (Ferrer, 1998, Ma et. al., 2004).
To optimize the energy consumption of aeration systems, the best blower control strategy is to supply the minimum amount of process air to the wastewater treatment, yet meeting substrate removal requirements. The adoption of a low-cost on-line off-gas measurement should be considered. Off-gas testing measures the exact mass transfer, not only an effect of it, therefore offering a new tool for accurate energy calculations. In addition, a time-series of off-gas measurements offers a tool for monitoring the decline in αSOTE with diffuser fouling, therefore it offers valuable information on the aerators' condition.

Conclusions

This paper demonstrates the capability of real-time off-gas analyzers to measure oxygen transfer (therefore, energy consumption), and their potential for an on-line feedback control system for aeration systems. The results of 24-hour experiments showed that oxygen transfer efficiency is negatively correlated with air flowrate, and α-factors are negatively correlated with the plant load (COD), which are consistent with previous field observations. The energy savings from the diffuser cleaning were also calculated based upon the two off-gas tests in different time points (before and after cleaning). Diurnal cycle patterns corroborate the evidence that load (i.e., surface active agents) depresses oxygen transfer and α-factors (Rosso and Stenstrom, 2006b). The database we collected is also a valuable tool for accurate design and specification of aeration systems (air diffusers and blowers).

Acknowledgements

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Table 1. Results of off-gas tests and energy estimation

Tests	Results or properties	Process Tank (×4)		Polishing Tank (×2)	Total
		Section 1	Section 2		
Background	Section dimension (m^2)	17.3 × 28.8	17.3 ×28.8	85.3×11.4	1969
	Depth (m)	5.8	5.8	4.5	-
	Number diffusers	71(×4)	56(×4)	127(×4)	762
Test 0 (Reference)	Air flow rate (m^3s^{-1})	1.49	0.87	0.38	2.74
	αSOTE (%)	17.5	18.3	18.9	-
	Power/OTR (kWh/KgO_2)	0.13	0.10	0.29	0.13
Test 1 (Before cleaning)	Air flow rate (m^3s^{-1})	1.34	1.01	1.00	3.35
	αSOTE (%)	15.8	16.3	13.4	-
	Power/OTR (kWh/KgO_2)	0.14	0.13	0.34	0.17
Test 2 (After cleaning)	Air flow rate (m^3s^{-1})	1.16	0.89	0.70	2.75
	αSOTE (%)	18.6	18.5	10.82	-
	Power/OTR (kWh/KgO_2)	0.13	0.12	0.44	0.15

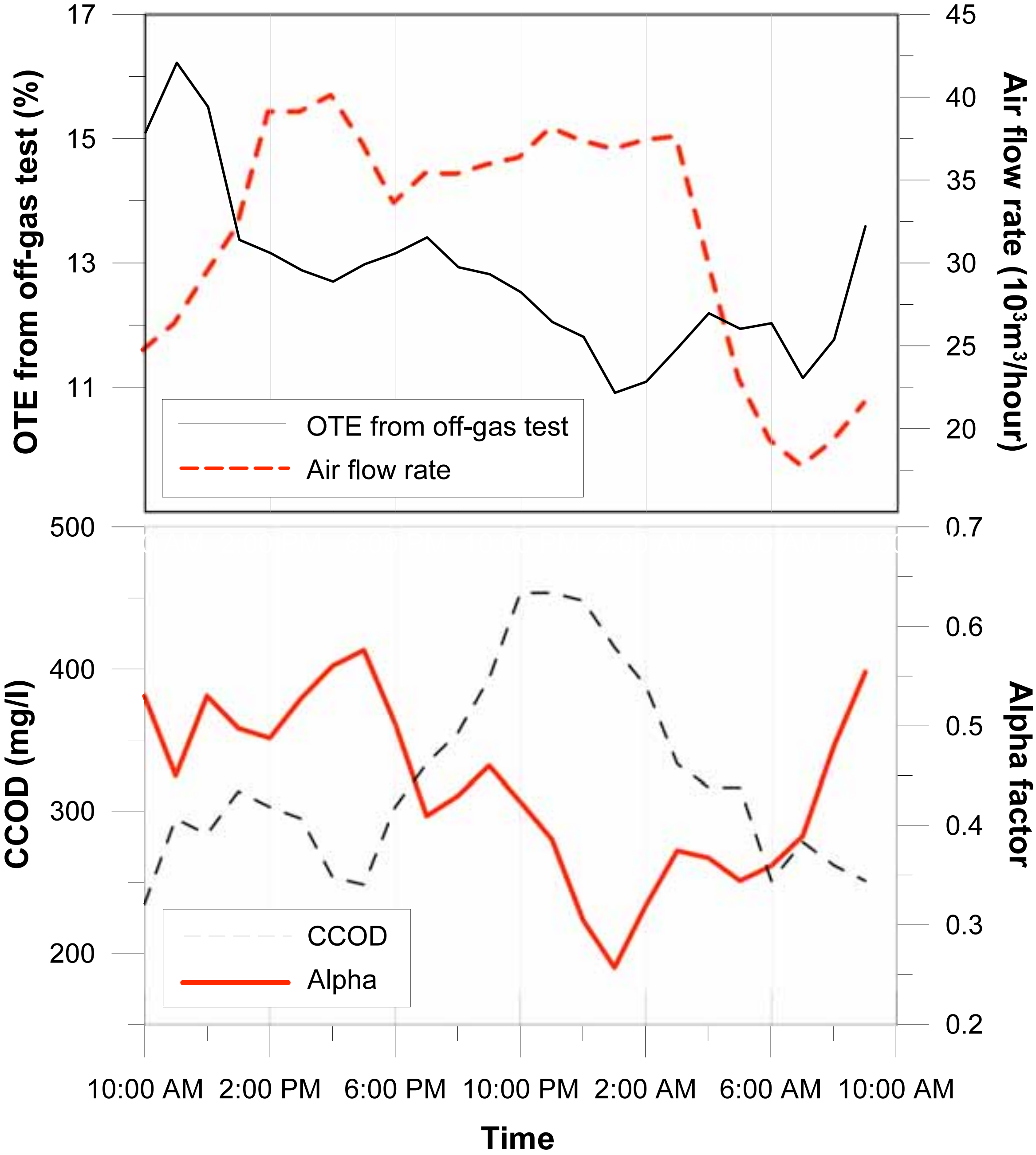
17
15
13
11
OTE from off-gas test (%)
45
40
35
30
25
20
Air flow rate ($10^3 m^3$/hour)
OTE from off-gas test
Air flow rate
500
400
300
200
CCOD (mg/l)
0.7
0.6
0.5
0.4
0.3
0.2
Alpha factor
CCOD
Alpha
10:00 AM
2:00 PM
6:00 PM
10:00 PM
2:00 AM
6:00 AM
10:00 AM
Time

Figure 1. (a) Oxygen transfer efficiency (OTE) and air flow rate calculated from off-gas testing during a 24-hr cycle in a 37800 m^3/day (10^7 gal/d) municipal wastewater treatment plant. (b) Carbonaceous COD (C-COD) and alpha-factor estimated from off-gas analysis, during the same period. Note the analogous patterns for the two graphs, which show that the off-gas reading (OTE) carries information on both AFR and load conditions (C-COD).

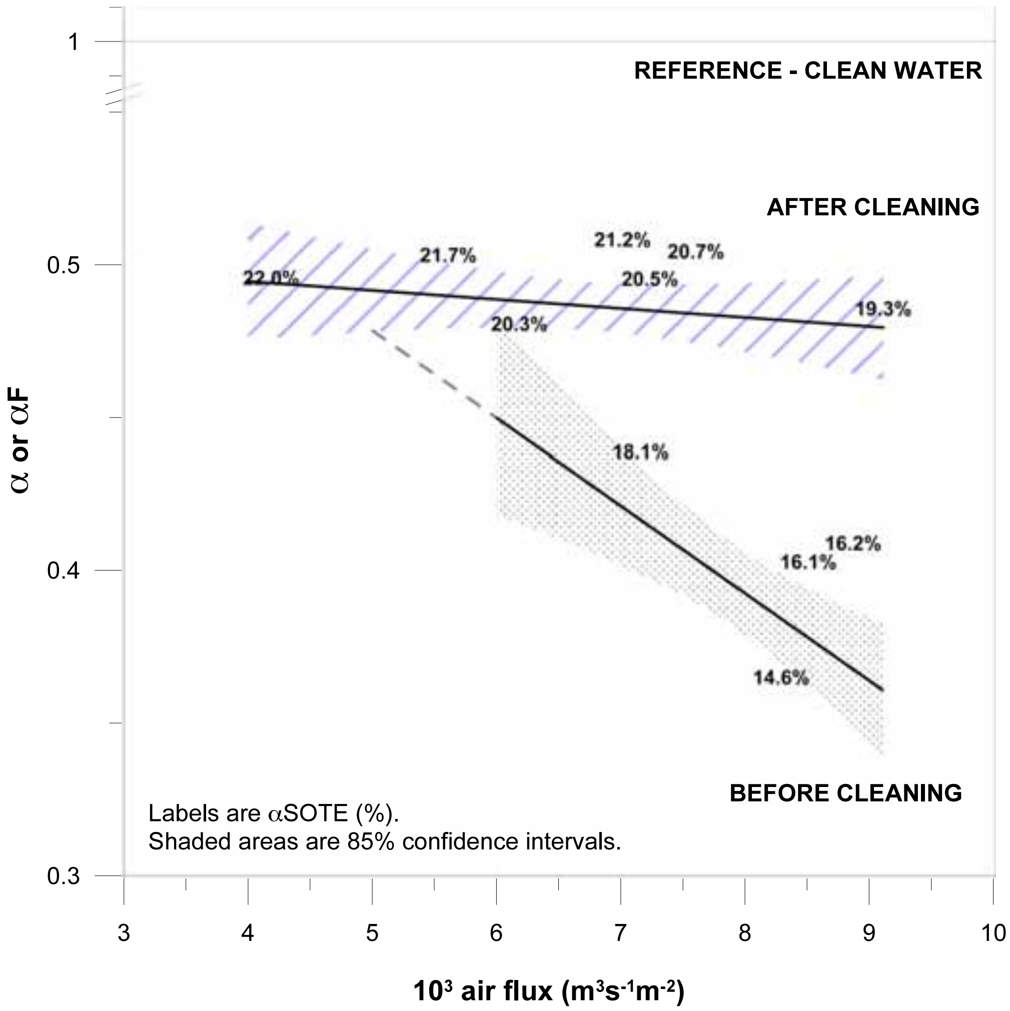

Figure 2. Correlation between standard oxygen transfer efficiency (SOTE) and diffuser air flux (curve zones represents 95% confidence). The upper part of SOTE is measured

from clean water tests, and the lower part is from off-gas tests (e.g. the difference represents the effects of contaminants and/or fouling/scaling); also note the increase of SOTE after diffuser cleaning.

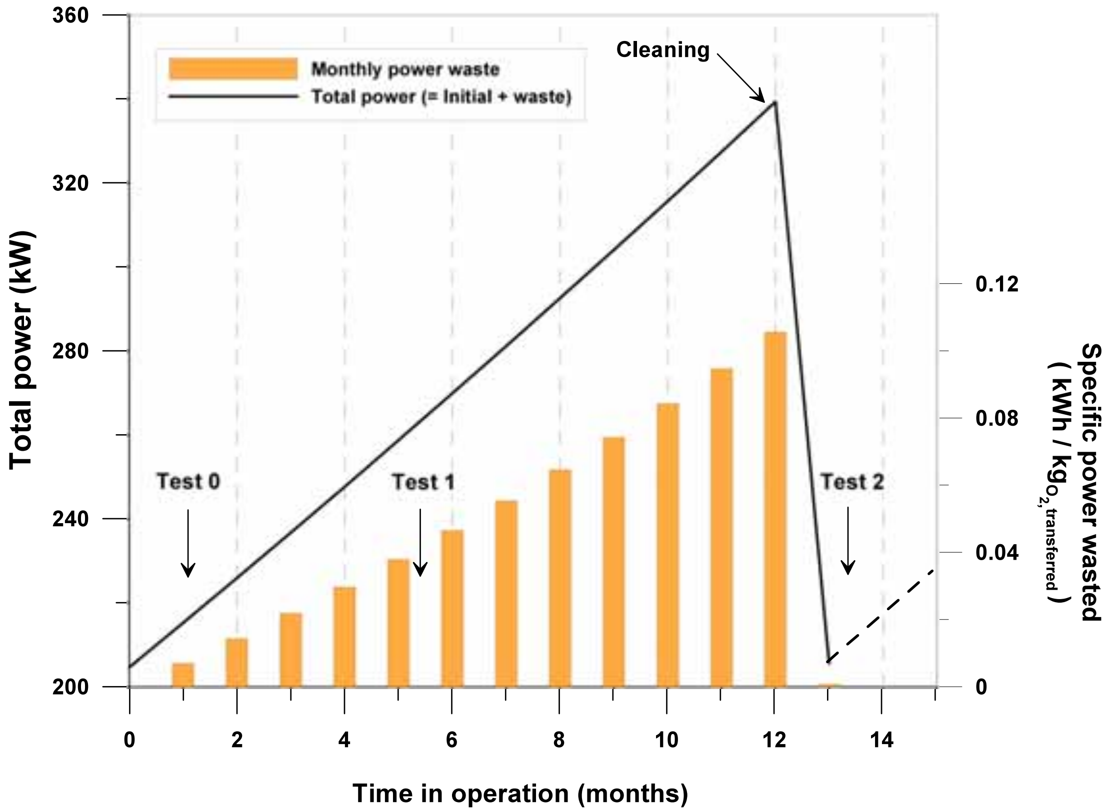

Figure 3. Total power and specific power wasted versus time in operation. Power waste = Total power - initial power, and the results are normalized per unit oxygen transferred. Note the rapid decline in power requirements after cleaning, almost to the initial value.

Documenting Improved Aeration Efficiency Using Off-Gas Analyses

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Abstract - Aerobic bacteria processes are the most common technology for municipal wastewater treatment. Their metabolism requires aeration, which is the most energy-intensive operation in a wastewater treatment plant (Rosso and Stenstrom, 2005). Aeration systems for municipal wastewater treatment plants are mainly full-floor configurations of fine-bubble diffusers, due to their favorable oxygen transfer rate (OTR, kg_{O2}/hr) per unit energy required (i.e., kg_{O2}/kWh_{needed}). The main pitfall of this aeration methodology is fouling/scaling, which causes a decrease in oxygen transfer efficiency (OTE, %) resulting in an increase in the energy cost per unit oxygen transferred (Rosso and Stenstrom, 2006a). The off-gas technique measures the mass transfer by analyzing the oxygen content in the off-gas stream. The mass balance between oxygen fed (21% mole fraction) and in the off-gas stream returns the oxygen transferred. The off-gas technique is the aeration efficiency measurement with the highest accuracy and precision (ASCE, 1997; Redmon et al., 1983).
We developed and built an automated off-gas analyzer which operates on-line and is self-calibrating. This device represents the highest degree of simplification, yet maintains the highest degree of measuring accuracy. For each measuring event, the automated electro-hydraulic circuit analyses reference air and off-gas, therefore calibrating to air oxygen concentration each time. The off-gas flow rate is recorded for each measurement, to allow a flow-weighted average of the results. Our full-scale testing campaign produced an extensive aeration efficiency database, which complements our previous extensive off-gas experience (Rosso et al, 2005).
Figure 1 shows a sample measurement recorded with our automated analyzer. The graphed plot contains both processed and unprocessed data (before noise filtering). The processed data have a step-pattern, due to a sequence of reference air/off-gas measurements. The off-gas readings always have a lower value than reference air, as expected, and become smaller in value during the diurnal load cycle of the plant, i.e. at the time when load reaches its minimum (and the air flow rate AFR its minimum), OTE is maximum (Fig.2). Alpha factors are reported here, due to the availability of clean water data for the location tested and reported in Fig.2. Although previously a diurnal cycle of OTE measurements was reported (Libra et al, 2002), this is the first report of alpha factors over a diurnal cycle. The patterns of alpha and carbonaceous COD (C-COD) have analogous behavior as OTE vs. AFR. This result shows that the off-gas reading (OTE) carries valuable information on AFR and load. For a given load, the off-

gas signal can be used, therefore, as a feedback control to regulate AFR to its minimum admissible value.
Our results show how on-line off-gas analyzers can be utilized as feedback control measurements for aeration system control. The diurnal cycle patterns also corroborate the evidence that load (i.e., surface active agents) depress oxygen transfer and alpha factors (Rosso and Stenstrom, 2006b). The large database we collected is a necessary tool for accurate design and specification of aeration systems (air diffusers and blowers). Moreover, results are reported in dimensionless form as efficiency loss curves over an extended period of time. These curves predict cleaning events and can be used to implement effective cleaning schedules that can result in large energy savings.

Key Words – Efficiency, energy, activated sludge, off-gas, aeration, wastewater.

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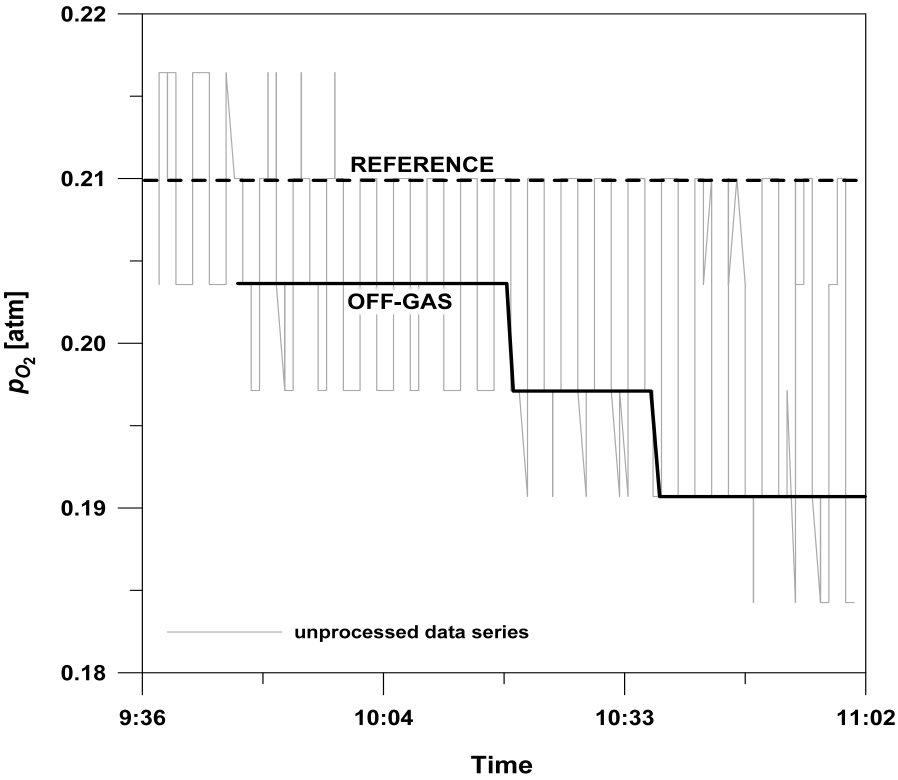

Figure 1. Sample measurement record with the automated off-gas analyzer. The oxygen transfer efficiency (OTE) is proportional to the partial pressure difference between reference and off-gas.

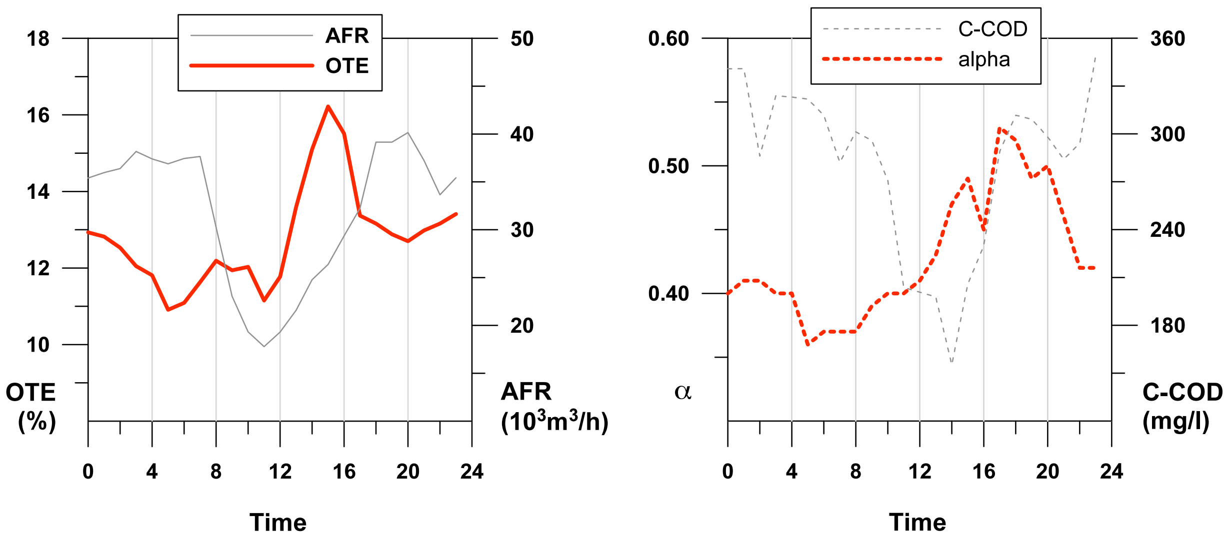

Figure 2. Oxygen transfer efficiency (OTE), air flow rate, alpha-factor, and carbonaceous COD (C-COD) during a 24-hr cycle in a 20 MGD municipal wastewater treatment plant. Note the analogous patterns for the two graphs, which show that the off-gas reading (OTE) carries information on both AFR and load conditions.