Real-Time Aeration Efficiency Monitoring in the Activated Sludge Process and Methods to Reduce Energy Consumption and Operating Costs

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ABSTRACT: Aeration is the most energy intensive unit operation in municipal wastewater treatment, and fine-pore diffusers have been widely used to minimize power consumption. Unfortunately, fine-pore diffusers suffer from fouling and scaling problems, which cause a rapid decline in aeration performance and significant increase in power consumption. Diffusers must be cleaned periodically to reduce energy costs. The cleaning frequency of diffusers is site-specific and its effectiveness can be evaluated with oxygen transfer efficiency (OTE) testing. Off-gas testing is the best technique for measuring OTE in real-time. Fine-pore diffusers have low α factors that are further reduced at high loading rate. A time-series of off-gas measurements were conducted to demonstrate the value of real-time OTE data for developing energy-conserving operating strategies. The observations confirm the inverse correlation between OTE and airflow rate as well as the economic benefits of diffuser cleaning. In addition, mathematic models were applied to simulate the transient oxygen uptake rate (OUR) and show the impact of varying load on OTE and aeration cost, especially when faced with time-of-day power rates. Regular diffuser cleaning can reduce average power costs by 18% and various equalization alternatives can reduce power costs by 6 to 16%. *Water Environ. Res.*, **81,** 2471 (2009).

KEYWORDS: aeration, off-gas test, oxygen-transfer efficiency, modeling, wastewater, energy.

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1. Introduction

Municipal wastewater treatment plants have been converted to fine pore diffusers that have resulted in significant energy savings. Fine pore diffusers work well but suffer from fouling and scaling problems, which rapidly decrease performance and significantly increase energy costs (Rosso and Stenstrom, 2006a). Fouled diffusers not only suffer a significant drop in oxygen transfer efficiency (OTE) but also have increased back pressure, typically defined as dynamic wet pressure (DWP, includes pressure drop and pressure to overcome surface tension). The combination of decreased efficiency and higher pressure drop increase power consumption and often degrade process performance. Because of different wastewater composition and treatment operations, the cleaning frequency of diffusers is site-specific, and may not be easily observable without off-gas measurements.

The off-gas technique developed by Redmon et al. (1983) is the process water OTE measurement with the highest accuracy and precision (ASCE, 1997), and it is the only technique that can determine OTE in real time. This technique measures the oxygen content in the air leaving the surface of the aeration tank, and the OTE is calculated by the mass balance of oxygen between ambient air (20.95% mole fraction) and off-gas. Libra et al. (2002) applied the off-gas method to compare the performance of several different aeration devices. Rosso et al. (2005) showed that transfer efficiency is a function of diffuser air flux and mean cell retention time (MCRT), based upon more than 100 tests at more than 30 plants. The impacts of fouling on plant economics and the need for diffuser cleaning have also been described (Rosso and Stenstrom, 2005).

Although OTE measurement using the off-gas technique does not require airflow rate measurement, it can be easily measured and used to calculate the oxygen transfer rate (OTR; kg O_2 transferred per hour), or the oxygen uptake rate (OUR; mg O_2/L/hour). Oxygen uptake rate is useful since it indicates the oxygen requirement, or the metabolism of microorganisms. With a time-series measurements of OUR, transient conditions in the bioreactor can be evaluated for activated sludge modeling and/or process control, such as optimization of the sludge recycle rate, contacting pattern and plant configuration (Stenstrom and Andrews, 1979); to verify the storage function of substrates (Goel et al., 1998; Third et al., 2004), the simultaneous uptake and growth of the heterotrophic and autotrophic biomasses (Beccari et al., 2002; Marsili-Libelli and Tabani, 2002), nitrification (Guisasola et al., 2003), denitrification (Puig et al., 2005; Third et al., 2004), and endogenous respiration (Koch et al., 2000).

Respirometers are the most common way of measuring OUR and have as their goal monitoring OUR in real-time over a wide-range of DO concentrations. These instruments may be limited to well-controlled environments because they usually measure at only a single point in an aeration tank. Examples of respirometry for process control include offline procedure and steady-state calculations (Beccari et al., 2002; Guisasola et al., 2003) and *in-situ* instrumentation for real-time control (Marsili-Libelli and Tabani, 2002; Sin et al., 2003; Spanjers et al., 1998), and are also

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being applied to sequencing batch reactors (SBR) (Baeza et al., 2002; Puig et al., 2005; Third et al., 2004). The difficulty of using these methods relates to the cost and maintenance requirements of a respirometer. The theory and benefits are sound but the methodology has not been applied routinely to a large number of treatment plants.

Off-gas analysis has been shown as an appropriate method to access the oxygen uptake rate under varying process conditions, and does not require a specific DO concentration for measurement. Therefore, a lightly loaded process at higher DO concentration or an overloaded process at near zero DO concentration can be evaluated. Yuan et al. (1993) and Tzeng et al. (2003) applied off-gas measurements of the covered high purity oxygen (HPO) activated sludge process reactors to calibrate the oxygen transfer functions in a structured model and to evaluate process control systems. Jenkins et al. (2004) used real-time off-gas analysis to calculate the change in airflow needed to affect a change in DO concentration, which was then used in a feed forward DO control strategy. Schuchardt et al. (2005) used real-time off-gas analysis for OTE and off-gas carbon dioxide concentration to separately estimate the heterotrophic and nitrifying loads.

Off-gas monitoring has rarely been coupled with mathematical modeling to reduce aeration costs, which is the goal of this paper. Off-gas monitoring can provide real-time measurement for several of the models' state variables, which creates a validated model to calculate aeration power cost. Aeration power is a function of aeration efficiency, DWP, power rates, and plant loads. Power rates often vary during the day, with late afternoons during warm months typically being the most costly. Plant flows vary with human activities, and large diurnal fluctuations in flowrate and wastewater composition are typical. If the increases in power consumption are in phase with higher power rates, then the cost of aeration can be quite large. Alternatively, if the peak in aeration power can be made to occur when power costs are minimal, savings are possible. The availability of real-time monitoring data of OTE, load, and power cost can be combined in a model that can be optimized to minimize power cost within the constraints of feasible plant operation.

In our experience, of the more than 30 plants evaluated with off-gas testing, only one plant was able to take advantage of off-peak power costs in any aspect of their operations. Part of the reason for this may be the unavailability of OTE measurements and inflexibility in process operations. The availability of simple, inexpensive off-gas analyzers (Stenstrom et al., 2007), increasing emphasis on conservation, and more frequent use of variable power pricing policies by power companies should encourage treatment plant operation to maximize power consumption during low-price periods, typically, late at night. The ability to take advantage of low-cost power will depend on both the availability of data and flexibility in plant operation. Offline equalization of wastewater flows, which has most often been used previously to improve pollutant removal efficiency or facilitate plant operations, is one tool for reducing peak loadings.

The objective of this paper is to demonstrate how real-time OTE monitoring can be used to reduce power costs. A simplified design of an off-gas analyzer with simplified digital electronics to provide real-time data is presented. A case study of a 10 MGD plant that has offline equalization is used to illustrate the potential savings. The plant was evaluated in multiple off-gas tests which were used to construct a demonstration of how to reduce power costs. A time-series analysis of the field experiments is presented and includes measurements of OTE, OTR, α factors in 24-hour cycles. Two examples are presented: the first shows the advantages of diffuser cleaning and the second shows the benefits of offline equalization.

2. Material and methods

Off-Gas Analysis. In order to compare the aeration performances of different aeration systems, OTE and OTR are normalized to standard conditions and are expressed as SOTE and SOTR (ASCE, 2006). Under process conditions, OTE is lower than in clean water, due to the effects of contamination, and alpha factor (α) is required to quantify this reduction. When OTE measured with off-gas analysis are converted to standard conditions, the result is defined as the αSOTE. When clean water data are available, the α factor can be calculated as:

$$\alpha = \frac{\alpha\mathrm{SOTE}}{\mathrm{SOTE}} \tag{1}$$

Former studies has reported different α factors for different aeration technologies, operating conditions (Capela et al., 2004; Rosso et al., 2005; Stenstrom and Gilbert, 1981), and the contaminants in wastewater (Rosso and Stenstrom, 2006b; Wagner and Pöpel, 1996).

The modern off-gas analysis and its instrument were developed by Redmon et al. (1983) under the sponsorship of U.S. EPA and ASCE. It uses a vacuum cleaner to collect the off-gas stream from the aeration tank thorough a floating hood, and an off-gas analyzer functions by sampling the off-gas trapped. If the CO_2 and water vapour are removed, eq 2 can be used to calculate OTE:

$$\mathrm{OTE} = \frac{O_{2\mathrm{in}} - O_{2\mathrm{out}}}{O_{2\mathrm{in}}} \tag{2}$$

Where

O_2 = mole fraction of oxygen in the gas streams (%)
subscript in = influent air supplied; out = off-gas

Using this technique, OTE can be measured without knowing the airflow rate. Knowing the airflow rate expands the utility of the results and can be easily measured by balancing the off-gas flow with the vacuum cleaner flow. By weighting the area of hood and tank surface, the air flux of the aeration system can be estimated, and oxygen transfer rate (OTR) can be calculated. The overall tank air consumption is calculated from the product of air flux and tank surface area. The OUR can be calculated from the gas flowrate, OTE and volume under aeration. Details on the methodology and recommended techniques are available elsewhere (ASCE, 1997).

The aeration energy was calculated based upon airflow rate and the efficiencies of the blowers and motors. A blower energy requirement of 0.049 kWh per unit m^3 (0.033 kW/SCFM) was calculated for this example using adiabatic compression (Metcalf and Eddy, 2003) with combined blower and motor efficiency of 0.61. Static pressure and line losses 146 kPa (21.2 PSI) and DWP from 9.0 to 13.8 kPa (1.3–2.0 PSI) as a function of airflow rate were based on plant measurements. These values along with airflow rate were used to calculate the aeration energy.

Field Experiments. Field tests were performed in a full-scale treatment plant with the capacity of approximately 38,000 m^3/day (10 MGD or 125,000 population equivalent). The plant uses an

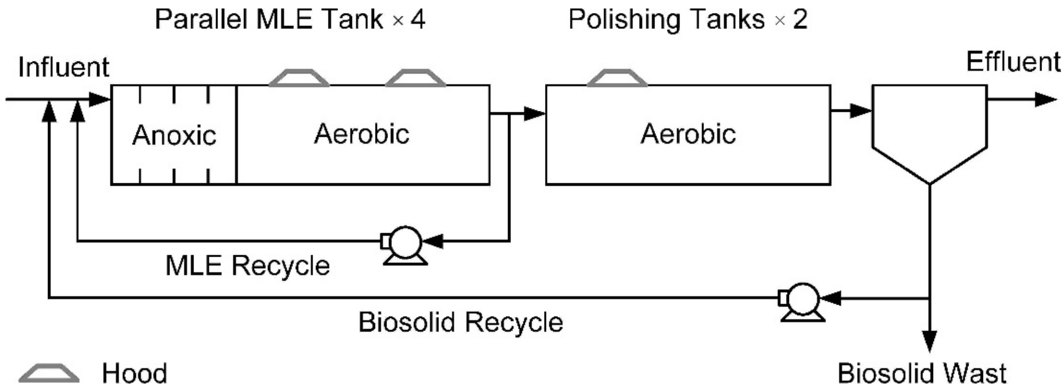

Figure 1—Schematic Diagram of the tested treatment plant (headworks, primary clarifier, equalization basin and disinfection facilities not shown).

activated sludge process that nitrifies and denitrifies using the modified Ludzack-Ettinger (MLE) concept, and the MCRT is controlled to approximately 7 days. Figure 1 shows a schematic diagram of the tested plant and the hood positions for 24-hour tests, and Table 1 shows the operating conditions of the plant. The total volume of aeration tanks is approximately 14,800 m^3. The anoxic zones comprise 33% of the total aeration tank volume. Two polishing tanks follow the four parallel MLE tanks and comprise 27% of the total volume. All aeration zones are equipped with fine-pore, membrane strip diffusers. The primary effluent contains 300 mg/L of total COD and 40 mg-N/L of ammonia on average, and is equalized by diverting peak flows to an offline storage tank (not shown in Figure 1), which are then pumped back during the low flow period. In this way peak loads on the process are reduced from 2800 m^3/hour to a maximum 1800 m^3/hour. For the 24 hour tests, primary effluent samples were collected hourly and analyzed for dissolved organic carbon (DOC), chemical oxygen demand (total COD), and ammonia nitrogen (NH_3-N). Organic nitrogen was measured using the plant's composite sampler and was assumed constant during the day, for the purposes of the simulations.

An initial off-gas test and two sets of 24-hour tests were performed. The initial test was performed 8 months after the diffusers were installed and was used to confirm the aeration system's performance. Hoods (2.2 m^2 area) were used in 8 positions in the initial test which lasted only 8 hours. Only three hood positions (see Figure 1) were used in the 24-hour tests, and the initial test was used to select hood positions that were representative of the tanks. The 24-hour tests involved only one process tank (Tank 4) and one polishing tank. The first 24-hour tests evaluated the diffusers under normal operation conditions, 13 months after the diffusers were installed, and the second 24-hour test was performed immediately after *in-situ* liquid acid cleaning, after 21 months of operation. The flow-weighted average values among the three hood positions are shown. The oxygen efficiency (OTE), air flux, DO, and the α factor were measured or calculated by the three hood positions,

To apply the 24-hour tests to the entire plant, the OTEs and OURs for each hood position were airflow weighted to create an average for Tank 4 and polishing basin 1. The averages were applied to the other tanks and basin. This is reasonable since the diffusers were installed at the same time, no cleaning had been performed, and the influent flow split among the tanks was equal (confirmed in the initial off-gas test).

Table 1—Operation background of tested treatment plant.

Properties	Values	
Volume of anoxic zone (m^3)	4,800	
Volume of aerobic zone (m^3)	10,000	
MCRT (day)	7	
pH	7.2	
MLVSS (mg/L)	2,300	
Flow conditions	**Range**	**mean**
Influent flow rate (m^3/hour)	0550–2800	1550
Equalized flow rate (m^3/hour)	0615–1800	1550
Total COD (mg/L)	155–350	300
DOC	34.5–83.5	57
COD/DOC	4.66–7.28	5.73
Ammonia (mg-N/L)	27–57	40
Organic Nitrogen (mg-N/L)	4–18	10
Wastewater temperature (°C)	22–27	24
Ambient air temperature (°C)	4–36	21

Off-gas Analysis. Figure 2 shows a schematic of the automated monitoring system. It is similar to the original analyzer (Redmon et al., 1983) but has several important differences to facilitate automation. The majority of the off-gas (~99%) travels through the flow tube and bypasses the rest of the instrumentation. The gas flowrate is measured by a hot wire anemometer or mass flow meter that produces no pressure drop in the flow tube upon insertion. This avoids the use of a vacuum cleaner to overcome the pressure drop associated with rotameters, and simplifies measurement since pressure balancing is not required. A small fraction (~16 mL/sec) of the off-gas passes through a drying column and a fuel cell that produces a signal that is proportional to oxygen partial pressure. A relay alternates flow between off-gas and air, which serves as a reference gas. The pressure balancing valve is used to provide the same pressure drop as the drying column and small flow meter. An op-amp is used to condition the signal which is then recorded. The output alternates between off-gas and reference gas, and the reference gas provides calibration for each measurement.

The measuring process can be switched on and off to provide the desired number of measurements; one measurement every 15 minutes appears to be adequate to capture all the process changes. For routine process monitoring, as proposed in this

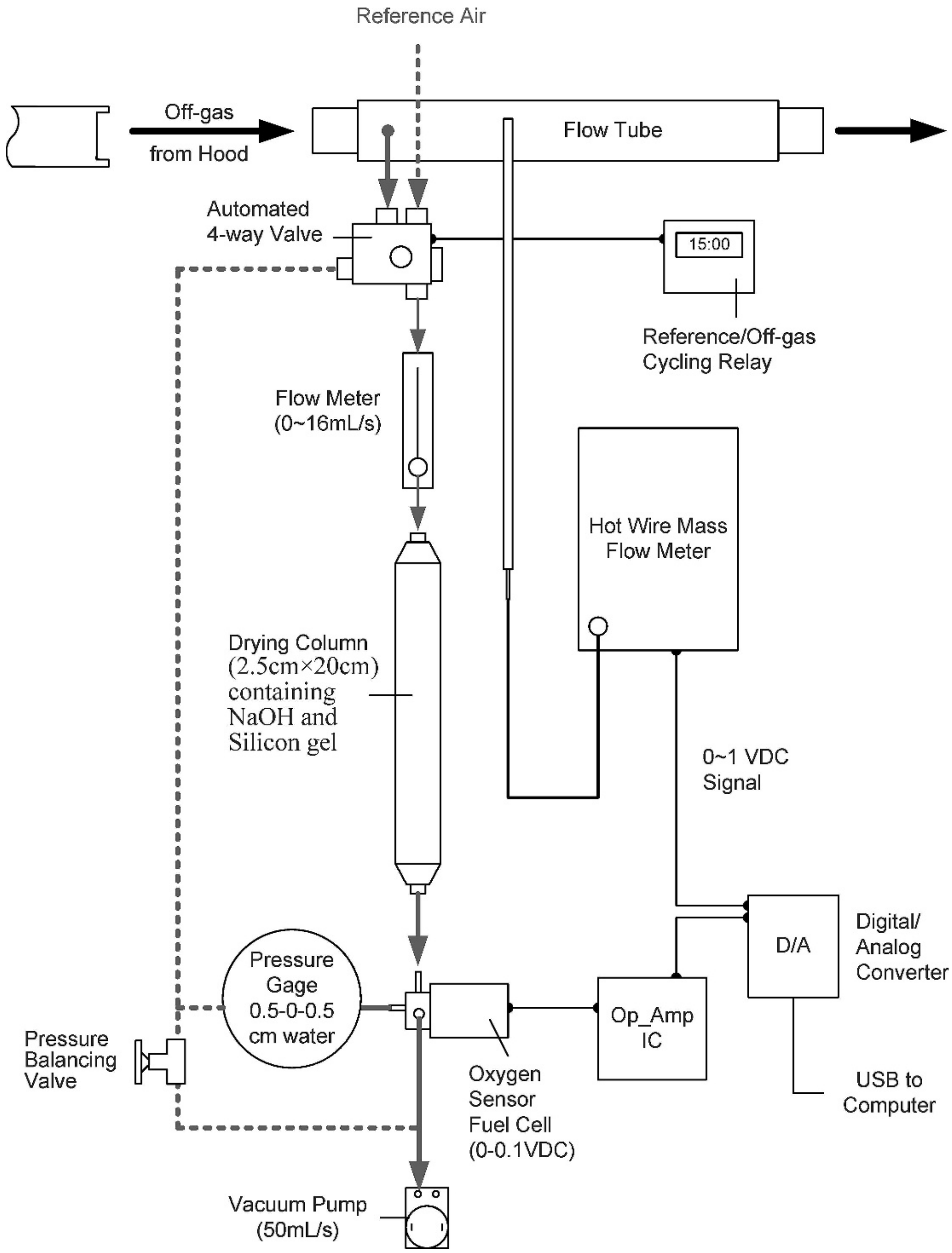

Figure 2—Schematic of a real-time off-gas monitoring system.

paper, a fixed hood in a single position can be used. Multiple hoods or hood positions must be used if is desired to obtain the spatial variability of OTE and OUR across an aeration tank. Development of this analyzer is funded by the California Energy Commission (CEC) and Southern California Edison Inc. The CEC insists that the products of the research project be in the public domain, and they are pursuing a contract for construction of inexpensive analyzers. More than one version of the real-time analyzer has been used in this project and they were compared to the conventional analyzer for quality assurance. A real-time analyzer is needed for 24-hour measurement, since it is impractical to keep operators working continuously. Stenstrom et al. (2007) provides more detail on the analyzer construction, including more specific information on the components.

Oxygen Uptake Rate Model. A dynamic model was developed to simulate the oxygen balance and energy conservation opportunities for a 24-hour cycle. The modeling approach was based on Lawrence and McCarty (1970) using Monod kinetics. It was desired to create the simplest possible model that adequately simulates the OUR. This allows a number of simplifications, such as considering total COD as opposed to soluble and particulate COD separately. The model simulates the transient conditions of five components: carbonaceous substrate (total COD), ammonia, nitrate, heterotrophic biomass, and nitrifier biomass. The volumetric flowrate of equalized primary effluent and pollutant concentrations measured from hourly grab samples were used to calculate the total oxygen demand, or the oxygen uptake rate (OUR). In this paper, OUR and OTR are different by definition: OTR represents the gas transfer capacity of aeration system, and OUR is the mass oxygen per unit volume consumed to degrade certain pollutants. The difference between the two parameters in a continuous-flow stirred tank reactor (CFSTR) is a function of non-steady state conditions as well as the sources of oxygen demand, and can be expressed as follows:

$$\frac{dDO}{dt} = \frac{1}{\theta_H}(DO^O - DO) + OTR - OUR_N - OUR_C - OUR_D \qquad (3)$$

Where

θ_H = hydraulic retention time (hour)
DO^O = influent dissolved oxygen concentration (mg/L)
OUR_C = OUR of substrate consumption (mg/L-hour)
OUR_N = OUR of nitrification (mg/L-hour)
OUR_D = OUR of biomass decay (mg/L-hour)

Wastewater aeration is commonly controlled at near constant DO, and the time constant associated with oxygen transfer ($\sim 1/K_La$, with K_La typically ranging from 2 to 10 hr^{-1}) is rapid compared to the time constants for substrate and biomass change. Therefore, the derivative term of DO in eq 3 can be assumed to be negligible, transforming the equation to a steady state or algebraic calculation.

In this paper, OTR in eq 3 was calculated from off-gas tests. Data collected from the three hood positions were compared to clean water data using relationships described in the ASCE/EWRI standards (2006, 1997), as follows:

$$OTR = \alpha \cdot \left[\frac{\beta C^*_\infty - DO}{C^*_{\infty 20}}\right] \cdot \theta^{T-20} \cdot SOTR \qquad (4)$$

Where

β = correction factor for dissolved solids (T^{-1})
θ = temperature correlation coefficient
C^*_∞ = saturated dissolved oxygen concentration $\left(ML^{-3}\right)$
super- or subscript of 20 = standard conditions at 20°C

The relationships between substrate consumption and biomass growth are based on Monod kinetics. For example, the mass balances of ammonia (S_{NH}) and autotrophic biomass (X_N) can be expressed as:

$$\frac{dS_{NH}}{dt} = \frac{1}{\theta_H} \cdot (S^O_{NH} - S_{NH}) - \frac{k_N S_{NH}}{K_N + S_{NH}} \cdot X_N \qquad (5)$$

$$\frac{dX_N}{dt} = \frac{1}{\theta_H} \cdot (X^O_N - X_N) - \frac{X_N}{\theta_X} + Y^{NH3-N}_{XN} \cdot \frac{k_N S_N}{K_N + S_N} \cdot X_N - K_d \cdot X_N \qquad (6)$$

Where

k_N = maximum uptake rate of NH_3-N (gNH_3-N/gCOD-day)
K_N = half velocity coefficients of NH_3-N (mg-N/L)
K_d = decay coefficient (gVSS/gVSS-day)
θ_X = mean cell retention time (day)
Y^{NH3-N}_{XN} = mass yield of X_N on NH_3-N (gCOD/gNH_3-N)

Balances for heterotrophic substrate consumption and nitrite oxidation can be written in a similar fashion. Since nitrite was never observed, the nitrogen balance can be further simplified by considering it as a single step process with ammonia oxidation limiting.

The OUR needed to consume each substrate is equal to the growth rate with appropriate stoichiometric yields, and the consumption for ammonia can be written as follows:

$$OUR_N = Y^{NH3-N}_{DO} \cdot \frac{k_N S_{NH}}{K_N + S_{NH}} \cdot X_N \qquad (7)$$

Where

Y^{NH3-N}_{DO} = mass oxygen demand of nitrification (gO_2/gNH_3-N)

Heterotrophic OUR is calculated in a similar fashion but the yield term is slightly different because the carbonaceous substrate (S) is defined in units of total COD (mg/L) or oxygen equivalents (Stenstrom and Andrews, 1979), as follows:

$$OUR_C = Y^S_{DO} \cdot \frac{k_S S}{K_S + S} \cdot X \qquad (8)$$

Where

Y^S_{DO} = mass oxygen demand of heterotrophic growth (gO_2/gCOD)

k_S = maximum substrate uptake rate (gCOD/gCOD-day)

K_S = half velocity coefficients of heterotrophic growth (mg/L)

Similarly, the oxygen consumption of biomass decay can be calculated by the decay coefficient as:

$$OUR_D = Y^X_{DO} \cdot K_d \cdot X \qquad (9)$$

Where

Y^X_{DO} = oxygen demand of decay (gO_2/gCOD).

The oxygen consumption from the decay of nitrifier biomass is assumed negligible.

Therefore, OTR can be obtained by substituting the oxygen consumption of COD degradation (eq 7), nitrification (eq 8), and cell decay (eq 9) into eq 3, and can be calculated as:

$$OTR = \frac{1}{\theta_H} \cdot DO + Y^S_{DO} \cdot \frac{k_S S}{K_S + S} \cdot X + Y^{NH3-N}_{DO} \cdot \frac{k_N S_{NH}}{K_N + S_{NH}} \cdot X_N + Y^X_{DO} \cdot K_d \cdot X \qquad (10)$$

Eq 10 uses total COD and the rate must be the average of the rates for soluble and particulate substrate. Deviation from this rate will occur a significant portion of the COD is stored and later oxidized because the simple model cannot mechanistically simulate storage products. Deviation was observed between the modelled and measured OUR, and we attribute it to the delayed oxidation of storage products. The precise definition of the storage products can be debated. The ASM 1 and ASM 3 and the Clifft and Andrews models have differing treatments of storage

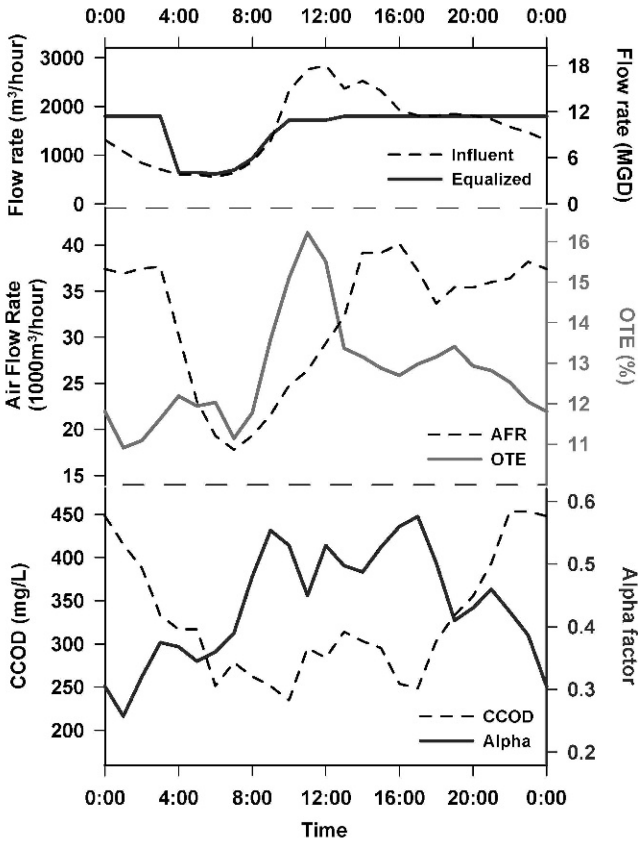

Figure 3—Influent, equalized volumetric flow rate, oxygen transfer efficiency (OTE), airflow rate (airflow rate), load, and alpha factor during a 24-hr cycle. αSOTE, airflow rate, and alpha factor were measured by off-gas tests.

products. For the purposes of this paper it is sufficient to notice that there is a delayed OUR associated with storage products. The delay in the exertion of OUR will be important because it delays or modifies the peak OUR.

The model was specifically developed to study the oxygen balance between oxygen demand and oxygen transfer, and to serve as a base to calculate aeration energy. We deliberately chose a model with few state variables to validate a simple linkage from measured data (off-gas analysis and a series of influent grab samples) to energy cost, by assuming constant DO and single reaction rate for influent COD.

3. Results and discussion

The 24-Hour Experiments. Figure 3 shows the volumetric plant flow before and after equalization, αSOTE, α factor, COD and airflow rate (airflow rate) measured or calculated for the first 24-hour transient test. The airflow rate increases dramatically during the periods of high loading period to maintain the required DO. The increase is larger than simple stoichiometry requires because of the reduced efficiency of the diffusers at higher airflow rate. This plant has a phase shift between COD and flow, and it is partly attributed to the offline equalization, which fills when the primary influent COD is high and empties when the primary influent COD is low. The α factor is also changing and is lowest when the COD is the highest. This occurs because the surfactants (detergents, soaps, fats, and oils) that are present in the influent and contribute to COD, take longer to degrade at higher concentration and have greater influence on aeration (Rosso and Stenstrom, 2006b). The reduction of efficiency with increased COD concentration is unfortunate, since the period of greatest aeration rate occurs at the lowest aeration efficiency. The top panel shows the wastewater flowrate and the impact of offline equalization; the peak flow is maintained less than 1800 m^3/hour (or 11.4 MGD) by storing the primary effluent during high flow periods. Results of the 24-hour test 2 showed similar pattern as test 1.

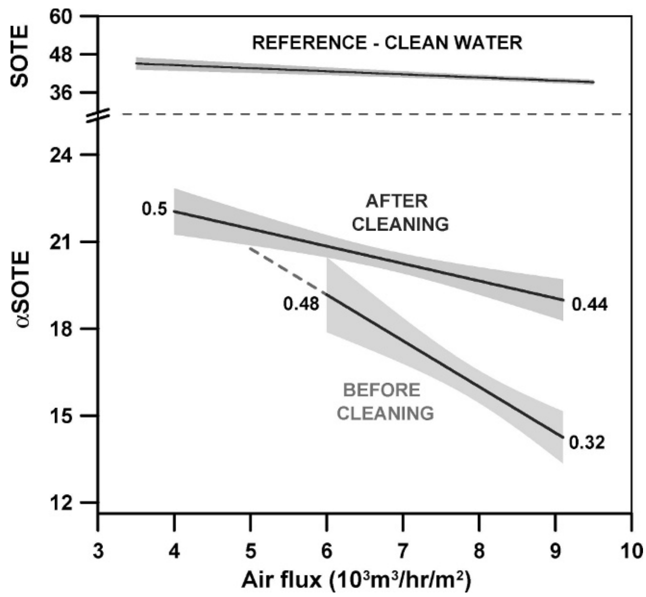

Figure 4—Correlation between SOTE, α, and diffuser air flux for both 24 hour tests. (curved zones represents 85% confidence interval and alpha factors are shown as number labels. Notice that the Y-axis is broken in two parts: the upper part (SOTE) is measured from clean water tests, and the lower part (αSOTE) is from off-gas tests (e.g. the difference represents the effects of contaminants and/or fouling/scaling); also notice that the increase of αSOTE after diffuser cleaning.

The large change in α factor should have special significance for designers. The alpha factor ranged from about 0.25 to 0.55. Aeration systems should be designed with the needed ''turn up'' and ''turn down'' capacity to accommodate such changes.

Figure 4 shows the data from the two 24-hour tests, before and after cleaning, plotted as a function of the αSOTE and air flux (airflowrate per unit of diffuser area, $m^3 \cdot hour^{-1} \cdot m^{-2}$ or SCFM/ft^2). The αSOTE is calculated from the OTE data shown in the middle panel of Figure 3 by adjusting the temperature, DO concentration, etc. to standard conditions. The clean water test results are shown at the top of Figure 4, and were measured in a warranty shop test. The α factors were calculated by dividing the αSOTE by the SOTE for the same diffuser air flux. The differences between clean and fouled α factors (fouled αfactors are often written as αF factors) is dramatic with αfor fouled diffusers declining at a greater rate with increasing air flux. This occurs because there are fewer open pores or slits with fouled diffusers, and the airflow per pore becomes greater, increasing bubble size. This and other impacts on alpha have been described in our other work (Rosso et al., 2005, Rosso and Stenstrom, 2006b).

Table 2—Matrix of mass yield from stoichiometry.

	Reacting compounds or products					
	S	S_{NH}	DO	X	X_N	Reaction kinetics,
Reactions	gCOD	g-N	gO_2	gCOD	gCOD	(mg/L/hour)
Heterotrophic growth	−1	−0.04	−0.51	0.49		$\frac{k_S S}{K_S + S} \cdot X$
Nitrification		−1	−4.33		0.17	$\frac{k_N S_N}{K_N + S_N} \cdot X_N$
Biomass decay		0.08	−1	−1		$K_d \cdot X$

Oxygen Demand Simulation. The previously described model was used to calculate the total OUR for microbial reactions. Table 2 shows a matrix formulation of the kinetics and yield coefficients of pollutants and treatment by-products for all the reactions, including heterotrophic growth, nitrification, and biomass decay. Table 3 shows the validated Monod kinetics used in our simulations. The parameters are within the range of commonly observed parameters (Metcalf and Eddy Inc., 2003, Poduska and Andrews, 1975) and were manually adjusted to provide the best fit with off-gas measurements.

Figure 5 shows the oxygen demand and oxygen transferred over a 24-hour cycle. The graph shows the three calculated OURs: heterotrophic growth, nitrification, and biomass decay. The OTR, measured by off-gas analysis, should equal the total OUR, but in the low loading part of the day, 3 a.m. to 10 a.m., more oxygen transfer occurs that is predicted by the model. The explanation is the delayed OUR associated with metabolizing storage products or particulate COD, which have a slower reaction rate, and is not included in the model. This creates a delay or shift in transfer and is frequently observed in full-scale plants. The top of Figure 5 shows the transient MCRT, which is a dynamic calculation of MCRT. The biomass waste rate is held constant, but other process aspects are not constant.

Equation 10 provided a good fit between observed OTR and OUR with the exception of peak and low flow periods. This occurs because the simple Monod model does not include the production and consumption of storage products (Andrews and Stenstrom, 1979). This is not necessarily a fault, since it allows for the observation of changes in storage product concentration, which becomes important when trying to equalize aeration energy consumption.

The degradation of stored mass during the low-loading period is caused by the changing F/M (food and mass) ratio. Substrate consumption in activated sludge is performed by a two-stage function: 85% of the organic substrate can be rapidly incorporated into the biomass but is not immediately degraded (Heukelekian et al., 1947), and are preserved as stored mass for later cell metabolism. Many structured models have adopted this two-stage reaction to perform better fitness with real conditions (Busby and Andrews, 1975; Cliff and Andrews, 1983; Gujer et al., 1999; Stenstrom and Andrews, 1979). The commonly used Lawrence and McCarty (1970) approach was selected for simplicity and the

Table 3—Monod kinetics of activated sludge model at 20°C.

Parameters	Value
1. Heterotrophic species	
Maximum uptake rate, k_S, gCOD/gCOD-day	6
Half-velocity of substrate, K_S, mg/L	30
Yield coefficient, Y, g COD/g COD	0.5
Decay coefficient, K_d, gVSS/gVSS-day	0.06
2. Autotrophic	
Maximum uptake rate, k_N, gNH_3-N/gVSS-day	1.08
Half-velocity of substrate, K_N, mg-N/L	1.05
Yield coefficient, Y_N, gCOD/gNH_3-N	0.17
Decay coefficient, K_{dN}, gVSS/gVSS-day	0.12

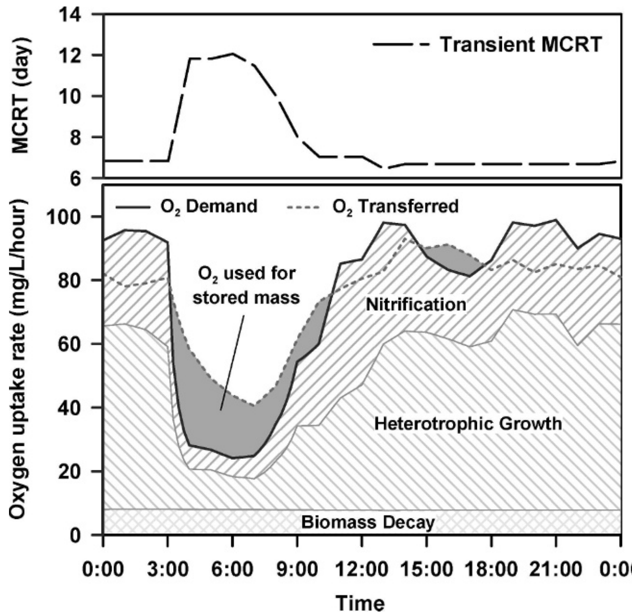

Figure 5—Simulated oxygen uptake rate versus the rate of oxygen transferred (measured by off-gas tests) during the 24-hour cycle. The fraction oxygen demands of various microbiological reactions (biomass decay, heterotrophic growth, or nitrification as labelled) are detailed in slash. The difference between O_2 demand and transferred, shown in the shaded area, represents the oxygen consumed to degrade the stored mass.

ability to show the importance of storage products. Although it does not simulate the rapid uptake of substrate as performed in structured models (Henze et al., 1987, Melcer et al., 2003, Tzeng et al., 2003), it provides sufficient information to calculate the oxygen demand of nitrification and heterotrophic growth.

The impact of storage product formation is to help equalize the OUR. After equalization, approximately 10% of the heterotrophic uptake occurs during the low flow period, which reduces the maximum OUR and increases the minimum OUR. This is helpful for controlling the plant, since the ''turn up'' and ''turn down'' ratios are reduced.

Remarks on Air Supply System. 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 is inhibited and the sludge composition may change, reducing the treatment efficiency or even causing process failures (i.e., low DO sludge bulking). Conversely, high DO may pose problems for denitrification zones (which require anoxic conditions), and represents excessive energy consumption (Ferrer, 1998; Serralta et. al., 2002). Many studies have focused on improvement of the DO control systems (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 instrument 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.

Application I. – Energy Savings by Optimal Cleaning of Fine-Pore Diffusers. A time-series of off-gas measurements offers a tool for monitoring the decline in αSOTE with diffuser fouling. This application shows a strategy to estimate the energy costs for diffuser system before and after cleaning processes using the results of our off-gas experiments. Diffuser maintenance is site-specific and can be between once every six months to more than 2 years, and the net present value of the energy wastage can be calculated. The most economically favourable cleaning schedule can be determined, and the methodology has been demonstrated by Rosso and Stenstrom, 2006a. Table 4 shows the average oxygen transfer data gathered from the three off-gas tests: Test 0 is the reference test, which was performed 8 months after diffuser installation; Test 1 was performed five months after Test 0 and Test 2 was performed immediately after cleaning. Our results suggest that after five months' operation oxygen transfer efficiency decreased from 18.3% to 16.3%, providing an increase of airflow from 240,000 m^3/day to 290,000 m^3/day. The cleaning procedure recovers the αSOTE from 16.1% to 18.6%, reducing energy requirements from 235 kW to 193 kW, or approximately 18% of the total power consumption. Furthermore, since Test 1 was performed eight months before diffuser cleaning and the conditions of diffuser fouling could be more serious during this period, the actual total saving must be greater than the calculated savings.

The net present worth of the energy wastage can be compared to the cleaning costs, after Rosso and Stenstrom (2005, 2006a). The power wasted (bar plot), normalized per kg of oxygen transferred, in the tested aeration tank is shown in Figure 6. The power wastage is defined as the power consumption exceeding the initial power requirement for new diffusers. The total power requirements (solid line), increases after start-up 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. If the cumulative wasted power costs approach the cleaning cost, cleaning should be performed.

Table 4—Results of off-gas tests (averages from various time and hood positions)

Properties	Test 0	Test 1	Test 2
Diffuser conditions	Reference	Before cleaning	After cleaning
a. Plant conditions			
DO (mg/L)	1.6	1.9±0.6	2.5±1.0
Temperature (°C)	27	22±0.3	27±0.3
b. Measured by off-gas tests			
αSOTE (%)	18.3	16.3	18.5
Air flux ($10^3 m^3/s/m^2$)	1.75	2.03	1.78
c. Calculated parameters			
Operational air flow rate (m^3/day)	240,000	290,000	240,000
Aeration energy (kW)	192	235	193

Application II. – Optimization of the Peak Power Loadings. In addition to quantifying energy wastage due to diffuser fouling, the real-time off-gas test provides useful information to assist plant operation. As discussed, aeration energy is a function of oxygen requirements, which vary with plant loads and during the diurnal load cycle. Equalization tanks are commonly used in wastewater treatment to compensate peak flows and to improve system stability for process control. Typically, equalization attempts to provide a uniform influent volumetric flow into the treatment process. In geographic locations where power cost varies with time of day or season, cost-savings and power savings are not necessarily the same,

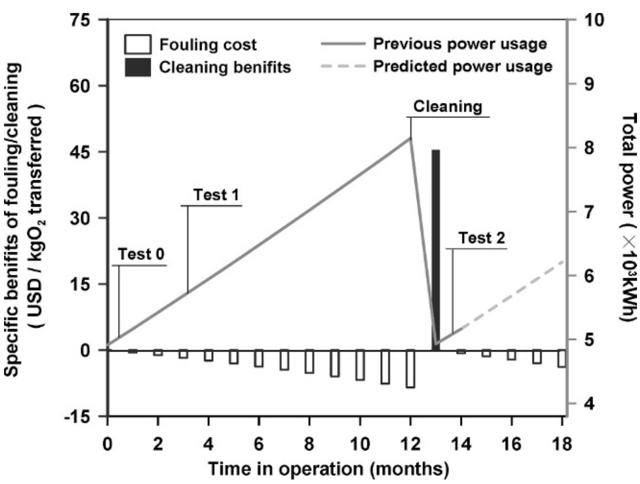

Figure 6—Energy expenditure of aeration cost. Total power consumption is calculated by the off-gas test results, which total power = initial power + power wasted. Costs and benefits are calculated based upon the power wasted. The power cost is 0.15USD/kWh and the results are normalized by unit mass of oxygen transferred.

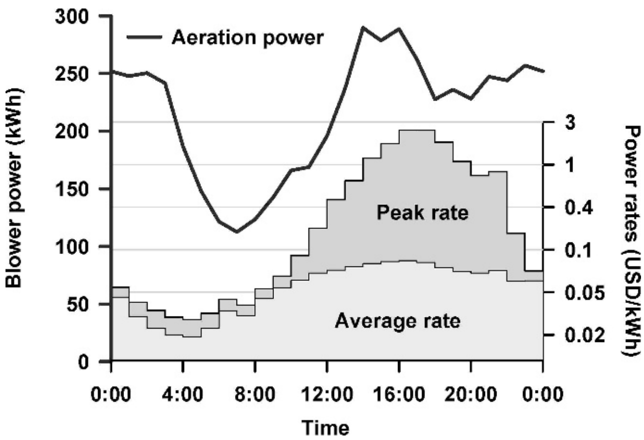

Figure 7—Energy consumption of blowers versus the hourly power rate at an average and a peak power season (Southern California Edison, 2005). The peak of power usage for aeration occurred approximately at the same period with peak power rates, even after flow equalization.

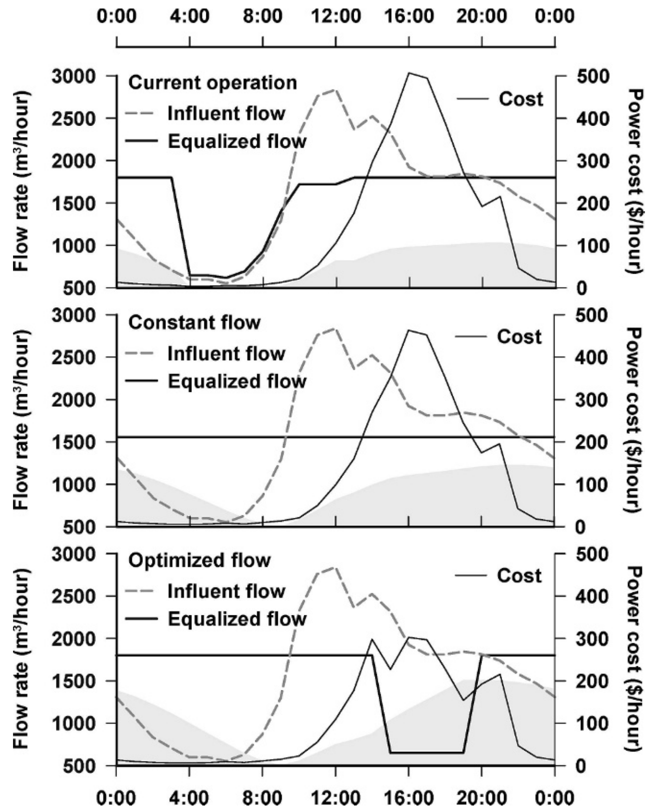

Figure 8—Energy saving practices by flow control. Current operation requires the lowest volume of equalization storage but may perform higher power costs on aeration. Two alternative strategies were suggested to reduce the treatment loadings at peak hours. Note: calculation of power rate was based on the peak summer season of California, U.S; and the shaded area represents the volume wastewater stored in the equalization basin.

as the following example illustrates. In this case, different strategies for offline equalization should be considered.

Figure 7 shows the hourly blower power drawn in the 24-hour cycle, obtained by the off-gas analysis (solid line), and the hourly industrial power rate (bars) in hot periods (peak rate) and average periods (average rate) (Southern California Edison, 2007). It is clear that the power consumption is not optimally managed: the high loading period of power consumption is in phase with the high-power-cost period during the afternoon (1 p.m. to 8 p.m.), and the cheapest power costs always occur at low loading period (4 a.m. to 10 a.m.). Significant savings can be realized if the plant flow is shifted to diurnal periods associated with lower power rates.

Using the previously described model, three offline storage scenarios were simulated: (1) current operation to limit peak plant flow to 1800 m^3/hr; (2) increased storage to create a constant plant flow, and 3) further increased storage to shift the peak power consumption to periods with lowest power rate. Current operation requires approximately 5000 m^3 of storage while options 2 and 3 require the storage volume to increase to 7,500 and 10,000 m^3, respectively. The power costs were calculated based on the power consumption times the power rates, for both peak and average conditions. In the simulations, the influent flowrates were slightly adjusted to simulate the extra OTR during the low loading period. Alpha factor is assumed to be constant, and SRT is the same as the current operation (7 days). Figure 8 shows the flowrates and power cost, but only for the peak power rate condition, while Table 5 shows power cost for both peak and average conditions, The case with no equalization was also simulated and shown in Table 5. The patterns of power costs for the low cost periods appear similar in the graphs because the rate is so low that the differences are not obvious; however, for high rate periods the optimized flow provides significant reduction in cost, which is obvious in Figure 8. It can be noted that longer hydraulic retention time in the aeration basins themselves can help create an equalized OUR, as shown in the middle panel of Figure 8.

Table 5 summarizes the power cost and the potential savings created by flow equalization. The results show significant savings of the three storage scenarios using flow equalization compared to the reference scenario with no flow storage. The various potential savings are shown for peak and average conditions, as well as a yearly estimate, based on two months at peak rate and five months each of summer and winter rates. The current operating strategy of limiting peak flows can saves up to 8% during the peak season, 5 to 6% during average winters and summers, and 6% on a yearly basis. If the flow can be adjusted to shift the low loading period, which ordinarily occurs at night, to the power rate peak hours in the afternoon, up to 31% of savings can occur in the peak season, or 16% on a yearly basis. In the studied treatment plant with an average ambient temperature of 21°C, treating 38,000 m^3/day (10 MGD), or approximately 125,000 P.E., moving the peak to the early morning will create $80,000 of power savings every year. Perhaps the most important conclusion is that complete equalization to constant plant flow, which greatly simplifies plant operation and improves effluent quality, produces significant power savings as well.

The power savings has an additional advantage for reducing green house gas emissions. Power companies typically maximize usage of their most efficient plants and minimize the use of their least efficient plants. Typically, night time operation uses as much

Table 5—Aeration costs of different plant operation strategy.

Operation Scenarios	High flow (m^3/hour)	Low flow period	Wastewater stored (m^3)	Power cost (USD/1000 m^3) Peak	Avg Summer	Avg Winter	Potential savings Peak	Avg Summer	Avg Winter	Yearly Savings	CO_2 Credit (g/kWh)
0. No equalization	2550	12am–7am	0	95.1	10.0	10.5	–	–	–	–	–
1. Current operation	1800	3am–7am	5,000	87.7	9.4	10.0	8%	6%	5%	6%	19
2. Constant flow	1550	–	7,500	80.5	8.9	9.7	15%	11%	8%	10%	36
3. Optimized flow	1800	2pm–6pm	10,000	65.9	8.5	9.5	31%	15%	10%	16%	59

Note: Unit of power cost = U.S dollars per unit volume thousand cubic meter wastewater treated.
Peak = summer season (June-Sept.) with temperature higher than 35°C.
Summer = summer season with average temperature = 24°C.
Winter = winter season (Oct.-May) with average temperature of 15°C.
CO_2 production for unit heat generation = 0.049 gCO_2/KJ.

hydro and nuclear sources as possible, and the oldest, least efficient plants (i.e., stand-by plants) are operated only during peak periods in the hottest weather. The heat rate for the most efficient natural gas burning plants is approximately 10,550 kJ/kWh (10,000 BTU/kWh). The least efficient gas burning plants in routine daily operation have a heat rate of approximately 13,700 kJ/kWh (13,000 BTU/kWh). During high demand times such as in the summer when system load is very high, the stand-by plants are used, which have a heat rate of approximately 19,000 kJ/kWh (18,000 BTU/kWh). The ability to shift peak power consumption to the early morning saves power and also reduces green house gas emissions by increasing the utilization of the most efficient power plants. If the flow is shifted to the low loading period, approximately 1200 kJ/kWh (1120 BTU/kWh) can be saved. The CO_2 savings or credit for equalization ranges from 19 to 59 g of CO_2 per kWh.

Conclusions

1) This paper illustrates the ability of a real-time off-gas analyzer to provide useful information to characterize plant operation and in particular to estimate aeration power consumption.
2) The results of 24-hour experiments showed that OTE versus OTR, and COD versus α factor are negatively correlated, which is the first observations of α factors as a function of diurnal plant loading. The results provide supporting evidence for previous observations that load (i.e., surface active agents) depresses oxygen transfer and α factors.
3) The impact of loading and diffuser airflow rates in response to increased loadings result in large changes in α factor. Designers need to be aware of the changes and the need to provide process flexibility to allow operators to respond to varying α actors.
4) The energy savings from diffuser cleaning were demonstrated using off-gas tests at different times (before and after cleaning). After cleaning, aeration power was reduced at least 18% due to increased oxygen transfer efficiency.
5) Flow equalization reduces aeration cost by 5 to 31% depending on the season and the available volume for storage. Completely equalizing flow to a constant rate saves nearly as much as shifting the peak loading to the low power rate periods (early morning hours). Yearly savings for the anticipated number of peak, summer and winter periods is 6% for peak limiting, 10% complete equalization and 16% for peak shifting.
6) The required offline storage, as a percent of average flow was 13% for peak limiting, 19% for complete equalization and 27% for peak shifting. The actual requirement will be site specific but should be similar.

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