Real-Time Efficiency Monitoring for Wastewater Aeration Systems

Shao-Yuan Leu\textsuperscript{a}, Diego Rosso\textsuperscript{b}, Pan Jiang\textsuperscript{a}, Lory E. Larson\textsuperscript{c}, Michael K. Stenstrom\textsuperscript{a}

\textsuperscript{a}Civil and Environmental Engineering Department, 5714 Boelter Hall, University of California, Los Angeles, Los Angeles, CA 90095-1593, U.S.A.
E-mail: syleu@ucla.edu (S.-Y. Leu); stenstro@seas.ucla.edu (M. K. Stenstrom).
\textsuperscript{b}Civil and Environmental Engineering Department, University of California, Irvine, Irvine, CA 92697, U.S.A.
\textsuperscript{c}Southern California Edison, Rosemead, CA 91770, U.S.A.

Abstract: Aeration is the most energy intensive unit operation in municipal wastewater treatment. To improve oxygen transfer rate, fine-pore diffusers have been wildly applied in aeration practice. However, during operation, this type of diffuser suffers from fouling and scaling problems, which cause a rapid decline in aeration performance and significant increase in energy consumption. Diffusers must be cleaned periodically to reduce energy costs. The cleaning frequency of diffusers is site-specific, and can be evaluated by oxygen transfer efficiency (OTE) measurements over time in operation. Off-gas testing is the only technique that directly measures oxygen transfer efficiency in real-time. This paper presents a time-series of off-gas measurements which demonstrate the value of implementing 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 caused by fouling. Our off-gas analyzer can be used to develop an aeration efficiency monitoring protocols, and an aeration feedback control system for blowers.

Keywords: Aeration; off-gas technique; oxygen-transfer efficiency.

INTRODUCTION

Municipal wastewater treatment plants have been converted to fine-pore diffusers which have resulted in significant energy savings. Fine-pore diffusers work well but have the pitfall of fouling and 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). A common way of quantifying OTE is the off-gas technique, which measures mass transfer by analyzing the oxygen content in the air leaving the surface of the aeration tank. The mass difference between oxygen fed (21\% mole fraction) and off-gas, which can be measured independently of off-gas flow rate, is used to calculate the OTE. If the airflow rate is also measured, the oxygen uptake rate (OUR) can be calculated as well as the overall plant loading, quantifying the oxygen requirements and the bacterial activity of the activated sludge process (Yuan, et al., 1993, Koch, 2000). This technique is applicable for measuring instantaneous wastewater treatment plant loadings, and to optimize blower systems. The off-gas technique is the process water aeration efficiency measurement with the highest accuracy and precision (ASCE, 1997).

The modern off-gas analysis and its instrument were developed by Redmon et al. (1983) under the sponsorship of US EPA and ASCE. It uses a vacuum pump to collect the off-gas stream from the aeration tank through a floating hood. The original off-gas procedure works very well, but requires an analyzer, the capture hood, a vacuum pump, and a crew of at least two to three experts to perform the analysis, which may take one to three days to perform for a typical activated sludge treatment plant. For this reason, off-gas testing is not routinely performed, but is used for periodic assessment of aeration efficiency or to collect data for plant design or upgrading. This paper presents a simplified, automated off-gas monitoring instrument (design data are in the public domain), which operates in real-time and is self-calibrating. In addition, we present the results of real-time off-gas testing and their
applications, which illustrate the capability of the new instrument for energy monitoring and its potential use for aeration control.

BACKGROUND

Oxygen transfer of fine-pore diffusers can be characterized by several definitions, i.e. oxygen transfer rate (OTR), 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°C, 0 mg/l of dissolved oxygen, 1 atm, 0 salinity). Therefore, OTR can be standardised as SOTR, and OTE as SOTE (ASCE, 2006).

The current standard method to quantify SOTR and SOTE is the unsteady-state clean water test (ASCE, 2006). In process conditions OTE 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 SOTE (ASCE, 1997):

$$\alpha = \frac{k_l a_{\text{process water}}}{k_l a_{\text{clean water}}}$$

The αSOTE is commonly used to compare process-water transfer efficiency and is adjusted to standard conditions for all parameter except the α factor. When clean water data are available, alpha-factors can be calculated as:

$$\alpha = \frac{\alpha_{\text{SOTE}}}{\text{SOTE}}$$

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).

To quantify the decreasing of α several techniques were developed; and after 15-year’s investigation, American Society of Civil Engineers (ASCE) published Standard Guidelines for In-Process Oxygen Transfer Testing in 1997. The Guidelines recommended three types of in-process water testing methods for diffused aeration system: 1) the non-steady method; 2) off-gas method; and 3) the tracer racer method. Among these techniques, the major advance described by the Standard Guidelines is the off-gas analysis method. It also describes but does not recommend two other methods, including methods based upon ex-situ oxygen uptake rate measurements and liquid-phase mass balances.

Methods based upon ex-situ oxygen uptake rate measurements, usually called the steady-state method, which uses a BOD bottle for oxygen uptake measurement, have severe limitations on applicability because of the inability to create conditions in a sample bottle that properly reflect conditions in an aeration basin. The inability to measure an accurate oxygen uptake rate creates artificially low or high oxygen transfer estimates, which have sometimes been explained as biologically enhanced transfer (Albertson and DiGregorio, 1975). The problems and a history of the errors introduced by ex-situ measurements have been discussed in detail by Mueller and Stensel (1990), who concluded that there was no evidence for biologically enhanced oxygen transfer rates in the activated sludge process. In-situ oxygen uptake measurements, such as those taken by process respirometers have been used extensively for process control, have not been extensively used to estimate process water transfer efficiency.

The off-gas analysis measures the aeration performance without changing conditions in the treatment plant 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. Rosso and Stenstrom (2005) showed how the transfer efficiency is a function of diffuser air flux and mean cell retention time (MCRT), based upon the dataset of more than 100 tests at
more than 30 plants in the USA. Additionally, they confirmed the contamination effects of surfactant on the alpha factor based on the same off-gas observation (Rosso et al., 2005). 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).

The analyzer functions by sampling the off-gas trapped by a floating hood on the surface of an aeration basin. If the CO₂ and water vapour are removed, Eq.3 can be used to calculate efficiency:

$$\text{OTE} = \frac{p_{O_{2,\text{in}}}}{p_{O_{2,\text{in}}}} - \frac{p_{O_{2,\text{out}}}}{p_{O_{2,\text{in}}}}$$

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

Using this technique, OTE can be measured without knowing the air flow rate. The air flow rate can be measured by balancing the off-gas flow an 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.

MATERIAL AND METHODS

Our laboratory has constructed several different off-gas analyzers, although all use the concept advanced by Redmon et al. (1983). In order to produce a simple analyzer that can be automated without the need for a highly trained operator, we used new digital devices and validated several prototypes in a full-scale municipal treatment plants. Field tests were performed in a full-scale treatment plant with the capacity of approximately 37800 m³/day (10 MGD). Table 1 presents a detailed description of the tanks. The plant contains four parallel process tanks (19 ft, or 5.8m in depth) and two aerated polishing tanks (15ft, or 4.5m deep). The aerobic zones of the process and polishing tanks are equipped with a fine-pore, strip-type diffusers. The off-gas hood positions are in the middle of the two aerobic sections and the first section of the polishing tank.

<table>
<thead>
<tr>
<th>Table 1. Characteristics of aeration tanks in tested treatment plant</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tank Properties</strong></td>
</tr>
<tr>
<td><strong>Section dimension (m²)</strong></td>
</tr>
<tr>
<td><strong>Depth (m)</strong></td>
</tr>
<tr>
<td><strong>Number diffusers</strong></td>
</tr>
</tbody>
</table>

Two sets of experiments were performed. The first experiment tested the aeration performance of diffusers under normal operation conditions, and the second test was performed immediately after in-situ liquid acid cleaning. The off-gas tests were done once per hour by the manual off-gas instrument to monitoring the oxygen transfer status in 24-hour cycles. The off-gas tests determined all the oxygen transfer parameters to compare with the influent wastewater conditions, i.e. the oxygen efficiency (OTE), air flux, DO, and $\alpha$ factor.

The results of off-gas experiments were used to estimate the energy costs for diffuser system before and after cleaning processes. To visualize the general idea of the aeration costs, several assumptions were made as follows: the blower energy requirement = 0.049 kWh/m³ air (0.033 kW/scfm), which were calculated using adiabatic compression equations (Metcalf and Eddy, 2003) with combined blower and motor efficiency = 61%, and the annual interest rate = 4%. The calculation results were used with an economic analysis spreadsheet, after Rosso and Stenstrom (2005, 2006a). This procedure allows the most favourable cleaning schedule to be determined.
RESULTS AND DISCUSSION

Figure 1 shows the behaviour of OTE compared to the air flow rate (AFR) 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 COD load) is highest, which is reflected in low OTE and $\alpha$ values. Alpha factors reported in Figure 1 were calculated from OTE and diffuser manufacturer’s clean water data. Although diurnal cycles of OTE measurements were reported previously (Libra et al, 2002), this is the first report of 24-hour observations of $\alpha$ factors. The patterns of $\alpha$ and carbonaceous COD (C-COD) have analogous behaviour as OTE and AFR. This shows that the off-gas monitoring can provide valuable information on AFR and load. For a given load, the off-gas signal can be used as feedback control to regulate AFR to its minimum possible value, and to estimate influent load concentration from real time OUR measurement. In addition to quantifying energy wastage due to the diffuser fouling, the real-time off-gas test provides useful information to assist plant operation.

Figure 1. Oxygen transfer efficiency, air flow rate, load, and $\alpha$ factor during a 24-hr cycle.

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 $\alpha$SOTE are negatively correlated with the air fluxes, which confirms the results of our previous long-term studies (Rosso et al., 2005). In addition, $\alpha$SOTE is approximately half of the clean water SOTE (labels on the graph). The process water $\alpha$SOTE has a different pattern for different time in operation: diffusers that have been in operation for a longer period without cleaning are fouled, which is shown by a more rapid decline in performance with increasing air flux (labelled “before cleaning” in Figure 2).
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 notice that the increase of SOTE after diffuser cleaning.

Figure 3 shows the oxygen requirement and oxygen transferred within the treatment system over a 24-hour cycle. The oxygen requirement calculated by influent total oxygen demand (TOD) was considered as the input signal of the system, and the oxygen transferred was recorded as output by off-gas monitoring. The difference between the two values (the shaded area) represents energy wastage due to over aeration. Notice that the TOD was calculated by the summation of carbonaceous and nitrogenous oxygen demands minus the COD from the average sludge wasting rate, so the oxygen requirement during the low loading period (3 to 6 am) is negative.

Figure 3. Rates of O\textsubscript{2} transfer and O\textsubscript{2} demand during the same cycle. Shaded areas are O\textsubscript{2} wastage.

The diurnal cycle patterns provide corroborating evidence that influent load (i.e., surface active agents) depresses oxygen transfer and $\alpha$ factors (Rosso and Stenstrom, 2006b). Table 2 shows the oxygen transfer data gathered from off-gas tests, and the energy
consumptions calculated with our plant-cost algorithm (Rosso and Stenstrom, 2006a). Our results suggest that the cleaning procedure improves oxygen transfer efficiency from 16.1% to 18.6%, thus reducing energy requirements from 235kW to 193kW, or 850 USD/day to 695USD/day. Since the first test was performed 8 months before cleaning and the diffuser fouling could be more serious during this period, the actual total saving must be greater than the calculated savings.

Table 2. Results of off-gas tests and energy cost estimation

<table>
<thead>
<tr>
<th>Tests</th>
<th>Process Tank (m$^3$s$^{-1}$)</th>
<th>Polishing Tank</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 0 (Reference)</td>
<td>1.49</td>
<td>0.87</td>
<td>0.38</td>
</tr>
<tr>
<td>Test 1 (Before cleaning)</td>
<td>1.34</td>
<td>1.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Test 2 (After cleaning)</td>
<td>1.16</td>
<td>0.89</td>
<td>0.70</td>
</tr>
<tr>
<td>SOTE (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 0 (Reference)</td>
<td>17.5</td>
<td>18.3</td>
<td>18.9</td>
</tr>
<tr>
<td>Test 1 (Before cleaning)</td>
<td>15.8</td>
<td>16.3</td>
<td>13.4</td>
</tr>
<tr>
<td>Test 2 (After cleaning)</td>
<td>18.6</td>
<td>18.5</td>
<td>10.82</td>
</tr>
<tr>
<td>Power/OTR (kWh/KgO$_2$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 0 (Reference)</td>
<td>0.13</td>
<td>0.10</td>
<td>0.29</td>
</tr>
<tr>
<td>Test 1 (Before cleaning)</td>
<td>0.14</td>
<td>0.13</td>
<td>0.34</td>
</tr>
<tr>
<td>Test 2 (After cleaning)</td>
<td>0.13</td>
<td>0.12</td>
<td>0.44</td>
</tr>
</tbody>
</table>

The normalized power wasted in the tested aeration basin is shown in Figure 4. The power waste (bar plot) 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.

![Figure 4. 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.](image-url)
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 $\alpha_{SOTE}$ with diffuser fouling.

Conclusions

This paper illustrates the capacity of off-gas analyzers and its potential to provide useful information to develop an on-line feedback control system for blowers. The results of 24-hour experiments showed that OTE vs. OTR and Carbonaceous COD vs. $\alpha$ factor are negatively correlated, which is consistent with literature observations. The energy savings from the diffuser cleaning were also calculated based upon the two off-gas tests at different time points (before and after cleaning). The diurnal cycle patterns corroborate the evidence that load (i.e., surface active agents) depresses oxygen transfer and $\alpha$ factors (Rosso and Stenstrom, 2006b). The database we collected is a valuable tool for accurate design and specification of aeration systems (air diffusers and blowers).

Acknowledgements

This research was supported by the California Energy Commission and Southern California Edison.

References