Monitoring the oxygen transfer efficiency of full-scale aeration systems: investigation method and experimental results

Riccardo Gori, Alice Balducci, Cecilia Caretti and Claudio Lubello

ABSTRACT

This paper reports the results of a series of off-gas tests aimed at monitoring the evolution of the oxygen transfer efficiency in an urban wastewater treatment plant (3,500 population equivalent) located in Tuscany (Italy). The tests were conducted over a 2-year period starting with the testing of the aeration system. It was found that in the absence of membrane-panel cleaning operations, the oxygen transfer efficiency under standard conditions in process water (αSOTE) dropped from 18 to 9.5% in 2 years. This gives rise to a 40% increase in the wastewater treatment plant annual energy costs. The on-site chemical cleaning of the diffusers allowed for an almost total recovery of the transfer efficiency (αSOTE equal to 16%). The use of the off-gas method for monitoring the oxygen transfer efficiency over time is therefore essential for enabling correct planning of the cleaning operations of the diffusers and for cutting the energy consumption and operating costs of the aeration system.

Key words | aeration system, fine-bubble, off-gas method, oxygen transfer, wastewater treatment

Riccardo Gori (corresponding author)
Alice Balducci
Cecilia Caretti
Claudio Lubello
Department of Civil and Environmental Engineering,
University of Florence,
Via S.Marta,
3 - 50139 Florence,
Italy
E-mail: *riccardo.gori@dicea.unifi.it*

INTRODUCTION

Energy saving as a method to reduce operating costs and CO_2 emissions is becoming more and more important in wastewater treatment plants (WWTPs) (Libra *et al.* 2002). Since in a conventional activated sludge plant energy demand is largely dominated by the aeration (Rosso & Stenstrom 2005), considerable savings are possible by optimising its design and operation. At present, the fine-bubble aeration system is the most widely used in European and North American WWTPs. The use of these devices offers numerous advantages including energy savings of about 50% compared to the coarse-bubble aeration systems (Stenstrom *et al.* 1984). However, due to the chemical nature and morphology of the materials making up the membrane, they are subject to fouling and scaling which can affect their operation and reduce the benefits of their utilisation in the long term (US EPA 1989).

The energy consumption of the aeration system depends both on the efficiency of its components (e.g. blowers), and on the characteristics of the wastewater, and it is not usually possible to predict the aeration system's behaviour under process conditions. It is therefore necessary to perform a series of measurements to verify the aeration system's behaviour in operating conditions. For this purpose several methods have been developed over the years. Among the available methods, the off-gas method has proved to be an effective technique that offers numerous advantages for testing diffused air aeration systems (Redmon & Boyle 1988; Iranpour *et al.* 2000; Capela *et al.* 2004).

In many countries, the issue of energy end-use efficiency has become so important that it is now incentivised and governed by regulations and standards. In Italy, the water sector has been classified as one of the 'strategic' sectors and the measures for improving energy efficiency are certified via the issuing of 'Energy efficiency certificates' ('white certificates'). Some of the interventions which are recognised for the purpose of issuing the white certificates concern the aeration system and include the replacement of mechanical aerators with fine-bubble aeration systems and the installation of electronic devices (inverters) for adjusting the frequency and the power in electric motors.

This article reports the results of three off-gas test campaigns conducted on a WWTP in Tuscany in order to quantify the efficiency of the oxygen transfer of the aeration system consisting of membrane panels. Particular attention

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has been paid to the economic savings deriving from the correct management of the aeration system. The tests were conducted within the AERE project ('Increasing the energy efficiency of wastewater treatment plants' financed by the Italian Ministry of the Environment and the Protection of Land and Sea), whose aim is to develop a prototype and a method for monitoring the oxygen transfer efficiency in operating conditions by means of the off-gas method.

MATERIALS AND METHODS

Off-gas method

The off-gas method was developed by Redmon & Boyle (1988) and is based on a gas-phase mass balance for directly measuring the efficiency of oxygen transfer in aeration systems under process conditions (ASCE 1997). The mass balance is performed by making a comparison between the oxygen content in a flow of atmospheric air (reference) and in an off-gas flow withdrawn from above the process tanks. See Figure 1 for a schematic layout of the system.

The off-gas test campaigns were conducted using an analyser developed by the Civil and Environmental Engineering Department of the University of Florence in collaboration with the Civil and Environmental Engineering Department of the University of California – Irvine.

This instrument is equipped with a combustible chamber that makes it possible to measure the oxygen content in the gas flows, a column ($h = 0.255$ m, $d = 0.025$ m) for absorbing the CO_2 and the water vapour present in the gas flows, a hot wire anemometer for measuring the off-gas uptake captured by the hood, and a valve for choosing between sending the ambient air and the off-gas into the test circuit. The signals coming from the oxymeter and the anemometer are automatically acquired every 0.05 s using an acquisition data card (National Instruments, sbRIO-9632). In order to collect the oxidation tank off-gas, a rectangular PVC hood was used with a 0.53 m^2 capturing surface, fitted with a hose with a 0.038 m diameter that allows for conveying the off-gas towards the analyser. The choice of instrumentation, in particular the shape and size, was dictated by the need to provide a system ensuring easy transport and handling due to numerous tests to be conducted on different plants.

The performing of an off-gas test campaign foresees the positioning of the collection device in different points on the surface of the oxidation tank according to a sampling plan established depending on the geometry of the tank and the aeration system. For each position, we analysed alternatively the ambient air and the off-gas for 4 min; this was the necessary time for obtaining steady-state conditions of the output signals from instruments.

The following parameters are measured during the analysis: the off-gas flow rate, the oxygen concentration in the gas phase, the dissolved oxygen (DO) concentration in the liquid phase, the atmospheric pressure, and the temperature of both the off-gas and the process wastewater. The recorded data allow the calculation of the oxygen transfer efficiency by means of Equations (1) and (2) under process

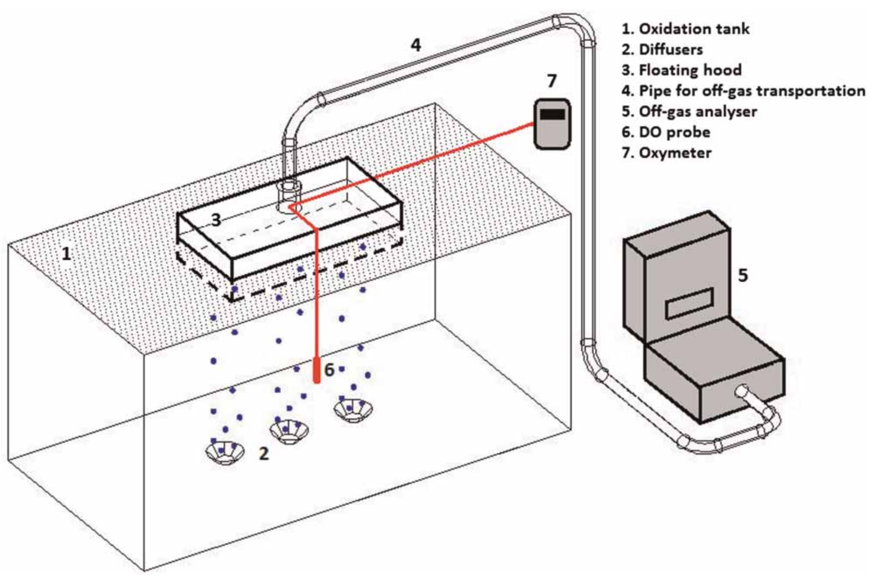

Figure 1 | Functional off-gas test diagram.

conditions (OTE) and in standard conditions for both new (αSOTE) and used (αFSOTE) diffusers, respectively:

$$\mathrm{OTE} = \frac{Y(O_{2,\mathrm{ref}}) - Y(O_{2,O-G})}{Y(O_{2,\mathrm{ref}})} \cdot 100 \quad (1)$$

$$\alpha\mathrm{SOTE}\ (\text{or}\ \alpha\mathrm{FSOTE}) = \frac{C_{s,20} \cdot \mathrm{OTE} \cdot \theta^{(20-T_W(^\circ C))}}{\beta \cdot C_{s,T} - \mathrm{DO}} \cdot 100 \quad (2)$$

where OTE: oxygen transfer efficiency in process conditions (%); $Y(O_{2,\mathrm{ref}})$, $Y(O_{2,O-G})$: molar ratio of oxygen compared to the inert aggregates in the ambient air and the off-gas (%); θ: empirical temperature correction factor (here set at 1.024) (non-dimensional); β: coefficient that takes the wastewater salinity into account (here calculated on the basis of total dissolved solids content) (non-dimensional); $C_{s,20}$: concentration of oxygen saturation at 20 °C (mg/l); $C_{s,T}$: concentration of oxygen saturation in operating conditions (mg/l); DO: concentration of dissolved oxygen in the tank (mg/l); α: ratio of process to clean water mass transfer for new diffusers (non-dimensional); αF: ratio of process to clean water mass transfer for used diffusers (non-dimensional); SOTE: oxygen transfer efficiency in standard conditions for clean water (%).

In order to fit the experimental data into a broader framework of operation of the plant and the wastewater characteristics, the following parameters were also established at the same time as carrying out the monitoring of the aeration system: the concentrations of chemical oxygen demand (COD), ammonium, nitrites, nitrates and specific pollutants such as surfactants, that influence the oxygen transfer (Rosso *et al.* 2006), in both the oxidation tank influent and effluent.

Tested plant and tests conducted

The experimental tests were conducted in the oxidation tank of an urban WWTP of 3,500 population equivalent (P.E.) located in Tuscany (Italy). The contribution of industrial wastewater is negligible. This plant was designed to operate as a conventional activated sludge system for carbonaceous substrate removal and nitrification. The biological compartment consists of a single oxidation tank with a rectangular shape, 20 m long and 8 m wide, with side water depth of 3.6 m. Initially, this plant was equipped with a system of disk diffusers uniformly distributed on the bottom of the tank. In 2010, due to serious air diffusion problems, the aeration system was replaced with 24 high-performance membrane panels (sized 4 m by 0.18 m), arranged in four frames each containing six extractable panels (Figure 2). Currently, the oxidation compartment is operated in alternate-cycles mode in order to have nitrification and denitrification in the same tank. The air flow is delivered in a timed manner with the time intervals periodically adjusted according to the purification process requirements. During the non-aerated periods mixing is assured by two mixers in opposite corners of the oxidation tank (Figure 2). The air flow rate supplied to the tank is not measured.

Three off-gas test campaigns were carried out on this plant, one in June 2010 and the others in May and July 2012. At the time of the first test the aeration system was fed by a positive displacement blower (Robuschi, RV80, flow rate 1105 Nm^3/h at 770 mbar) which was replaced before the second test by a positive displacement blower (Robuschi, RVT60, flow rate 485 Nm^3/h at 500 mbar) which has a lower power. The operating parameters and incoming wastewater characteristics on the day of testing are summarised in Table 1.

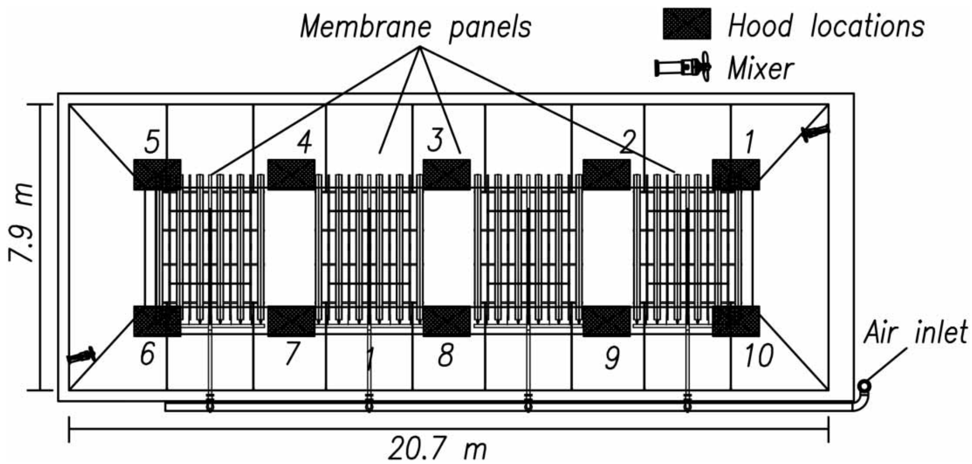

Figure 2 | Diagram of the test tank indicating the sampling locations (from 1 to 10) and diffuser mixer positions.

Table 1 | Characteristics of the WWTP influent and effluent

Test	COD (mg/l)	$N\text{-}NH_4^+$ (mg/l)	$N\text{-}NO_2^-$ (mg/l)	$N\text{-}NO_3^-$ (mg/l)	Surfactants (mg/l)	Flow rate (m^3/h)	T_w[a] (°C)
Influent							
June 2010	117	28.0	< 0.03	< 0.3	–	51.8	–
May 2012	189	28.6	< 0.03	< 0.3	6.1	49.5	–
July 2012	275	60.8	< 0.03	< 0.3	10.4	24.2	–
Effluent							
June 2010	26	< 0.1	0.16	12.1	–	–	20
May 2012	13	1.1	0.06	16.1	0.1	–	18
July 2012	17	0.4	< 0.03	18.2	0.2	–	23

[a]Wastewater temperature in the oxidation tank.

According to the data gathered during the tests, we can see that the plant is effective for both the removal of organic matter and nitrification. Nitrogen removal ranges between about 40 and 70%; such a variability can be attributed to the ratio between aerobic and anoxic periods, which is not continuously regulated on the basis of the influent characteristics. Moreover, the COD/$N\text{-}NH_4^+$ ratio, which can affect the nitrogen removal is variable (range of 4.2–6.6 is consistent with the long-term observations of the plant manager). The sludge age of the plant was estimated to be about 44 d, and thus the plant can be considered to be of the extended aeration type.

In each test campaign the measurements were taken in 10 different locations inside the tank, as illustrated in Figure 2, so as to guarantee the most uniform coverage of the tank possible.

The total area sampled complies with the minimum coverage limit of 2% recommended by the guidelines (ASCE 1997). It must be noted that during the period elapsing between the first and the second tests, the blower of the plant was replaced with another with a lower power. Therefore it was not possible to make the aeration system work under exactly the same conditions even though steps were taken to ensure conditions as similar as possible for making the data comparable.

The first test was conducted in June 2010, immediately after the installation of the new membrane panels. The initial goal was to verify whether the new aeration system was able to guarantee the performance claimed during the sizing. The next test was conducted 2 years later, in May 2012, to see whether there had been any loss of efficiency over time especially since no cleaning operations had been carried out in the meantime. Finally, another test was conducted in July 2012 immediately after carrying out a cleaning operation of the diffusers with peracetic acid, without extracting the panels from the tank. Results of the off-gas tests were then used to assess the aeration efficiency recovery due to the cleaning.

RESULTS

The overall αFSOTE of the aeration system was obtained by weighting the local efficiency measured at each hood location by the gas flow rates collected in the sampling points. The average values describing the performance of the aeration system during the three campaigns are summarised in Table 2.

The test conducted in June 2010 confirmed that the membrane panels are characterised by high-performance oxygen transfer and the values provided by the manufacturer and used during the sizing are representative of the system under examination. From an analysis of the situations hypothesised during the design stage, which take all the specific site characteristics into account, it was in fact found that the test could be considered positive for αSOTE values higher than or equal to 15%.

After 2 years' operation there was a large reduction in the performance of the diffusers. This reduction was quantified, via use of the off-gas method, as a halving of the αSOTE

Table 2 | Results of the off-gas tests

Test	Conditions of the diffusers	DO (mg/l)	OTE (%)	αFSOTE[a] (%)	αF[a]
June 2010	New	4.62	9.8	18.0	0.53
May 2012	2 years' service	0.03	9.4	9.5	0.30
July 2012	Cleaned	3.70	9.2	15.8	0.46

[a]For new diffusers αSOTE and α.

registered with new diffusers. A loss of panel efficiency was conceivable after observing how the oxygen concentration in the tank was much lower than that found in 2010, and it was not possible to attribute this phenomenon to the lower air flow delivered to the system alone. Without using the off-gas method it was not possible to quantify the reduction in the transfer efficiency. It is important to highlight that the low DO concentration registered in the second test could affect the off-gas test due to simultaneous nitrification–denitrification. For this reason a nitrogen mass balance was carried out on a daily basis, and, even considering the denitrification rate constant all day long, we estimated that the amount of nitrogen produced from denitrification contributes less than 1% to the nitrogen already present in the off-gas. Consequently we neglected this contribution in the calculation of OTE.

The deterioration of the fine-bubble diffuser operating performance over time, which has been widely documented in literature, is caused by the formation of bubbles with larger dimensions due to the biofilm that deposits on the membrane of the diffusers (Rosso & Stenstrom 2006). In this specific case it is possible that the dirtying of the diffusers was accelerated by the change of operational management of the plant, establishing an anoxic phase during which the aeration system is turned off. Following the cleaning of diffusers, an increase equal to approximately 6% was observed in the αFSOTE. A pressure drop in the air delivery pipe from 456 to 390 mbar was also noted at the same time.

Table 3 shows a comparison between the off-gas flow rate and DO obtained in the same positions in different test campaigns. The flows recorded in May 2012 are systematically lower than those in 2010 due to both the different blower power between the tests and the fouling of diffusers. It can also be observed how this reduction is of the same magnitude for all the positions, and it can therefore be assumed that there were no diffuser groups that were affected to a greater extent by the aging effect, or areas of the tank more prone to biological deposits. After the cleaning operation a significant increase in the off-gas flow rate was recorded in seven position out of the 10 tested. Variability in the ratio between the air flow rate before and after the cleaning can be due to the following reasons: air distribution is not uniform (not even in the first test with new diffusers), and the effect of the cleaning procedure could have been not uniform. In addition the air is supplied to the aeration tank using only one pipe and therefore fouling of diffusers can influence the air distribution.

Data in Table 3 also show that the DO concentrations recorded in July 2012 were significantly higher than those registered in May 2012 for all points monitored (mean average of 3.7 and 0.03 mg/l, respectively). The results obtained therefore confirm what was already expressed for the oxygen transfer efficiency data and, namely, the positive outcome of the intervention performed.

The fact of being able to quantify the increases or losses of efficiency of the aeration system plays a vital role in the economic management of a plant, since it makes it possible to quantify the increases or reductions in the energy consumption linked to the operation of the blowers, and consequently, to the operating costs of the plant. Indeed, with the same oxygen required for the biological reactions, an increase in performance in the aeration system gives rise to a reduced air flow necessary to supply the tanks, and, as a result, lower power consumption by the blowers.

An economic analysis was then carried out in order to evaluate the effect of diffuser fouling on the treatment cost. We firstly considered the values set for the design of the aeration system: 34.2% for SOTE (from diffuser's technical sheet), 0.276 kgO_2/Nm^3 for the oxygen content in the air flow in normal conditions (W_{O2}), 0.55 for the αF-value, 290 Nm^3/h for the air flow rate, and 0.99 and 1.024 for the coefficients β and θ, respectively. For the comparison

Table 3 | Comparison of off-gas flow rate (OG-FR) and DO (mg/l) obtained during the tests

		Positions									
Test		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
June 2010	OG-FR	3.97	4.02	3.90	3.97	2.78	2.84	3.31	2.75	2.77	5.44
	DO	1.43	3.83	4.80	5.43	5.67	5.81	5.88	5.31	4.71	3.38
May 2012	OG-FR	0.45	0.40	0.36	0.29	0.56	0.48	0.67	0.56	0.49	0.50
	DO	0.01	0.07	0.01	0.04	0.01	0.04	0.06	0.05	0.03	0.01
July 2012	OG-FR	0.48	0.82	0.39	0.66	0.88	0.35	1.19	0.55	0.8	0.86
	DO	1.26	3.89	4.43	4.34	4.11	1.55	3.97	4.5	4.2	4.7

OG-FR of June 2010 is expressed in Nm^3/h. OG-FR of May 2012 and July 2012 is expressed as ratio to the corresponding value of June 2010.

Table 4 | Blower energy consumption with variations in αFSOTE

Test	αFSOTE (%)	Air flow[a] (Nm^3/h)	Blower power (kW)[b]	Energy (kWh/y)	$\frac{kWh}{kg\,COD_{rem}}$	Aeration cost (€/y)
June 2010	18.0	301	4.8	43,800	0.68	6570
May 2012	9.5	568	8.2	83,220	1.28	12,483
July 2012	15.8	343	5.0	50,808	0.78	7621

[a]Air flow rate necessary to guarantee an OTR = 11.6 kgO_2/h.
[b]Power required to ensure the necessary OTR in process conditions (estimation was carried out on blower's technical sheet).

purposes we considered the following conditions: DO 2 mg/l and temperature 20 °C; thus $C_{s,T}$ was set at 9.2 mg/l. The oxygen transfer rate (OTR) was then calculated using the following expression:

$$\mathrm{OTR} = \frac{\alpha\mathrm{FSOTE} \cdot Q \cdot W_{O2} \cdot \theta^{(20-T_W(^{\circ}C))} \cdot (\beta \cdot C_{s,T} - \mathrm{DO})}{C_{s,20}} = 11.6\,\mathrm{kgO2/h} \quad (3)$$

We then used the Equation (3) to estimate the air flow rate required to ensure the same OTR with the αFSOTE registered during the tests. The calculated flow rate and the pressure drop reduction measured after the cleaning operation were then used to estimate the power required by the blower in the different conditions, according to its technical sheet (see Table 4).

Results of the economic analysis are summarised in Table 4. It can be observed how a reduction in the αFSOTE value from 18.0 to 9.5% gives rise to an increase in management costs by approximately €5,900/y. The recovery of the aeration efficiency due to the cleaning allows a significant reduction in the annual energy consumption and a saving of about 40% of the aeration cost with respect to the worst case. In terms of environmental effects, considering a specific 0.406 $kgCO_2/kWh$ as specific emission value (IEA 2012), the energy saving obtained with cleaning of diffusers corresponds to 13.2 tCO_2/y and 3.76 $kgCO_2/y$ P.E.

CONCLUSIONS

This paper shows the results of a case study on the use the off-gas method, and on its subsequent energy and economic savings. This method was applied to a plant in Tuscany (Italy) equipped with micro-perforated membrane panels, and it was found that after 2 years' operation, the oxygen transfer efficiency dropped from 18 to 9.5%. After washing the diffusers with peracetic acid it was possible to recover the majority of lost efficiency and re-establish values resembling the initial ones.

It was observed how a delay in cleaning the diffusers gave rise to a relevant increase in operating costs, equal to approximately €5,900/y for a plant with 3,500 P.E., which therefore cancels all the benefits of using high-performance fine-bubble aeration systems. The economic, energy and environmental savings resulting from correct management of the aeration system are therefore high and tangible, even for small-sized plants.

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