Monitoring the variations of the oxygen transfer rate in a full scale membrane bioreactor using daily mass balances

Y. Racault, A.-E. Stricker, A. Husson and S. Gillot

ABSTRACT

Oxygen transfer in biological wastewater treatment processes with high sludge concentration, such as membrane bioreactor (MBR), is an important issue. The variation of α-factor versus mixed liquor suspended solids (MLSS) concentration was investigated in a full scale MBR plant under process conditions, using mass balances. Exhaustive data from the Supervisory Control And Data Acquisition (SCADA) and from additional online sensors (COD, DO, MLSS) were used to calculate the daily oxygen consumption (OC) using a non-steady state mass balance for COD and total N on a 24-h basis. To close the oxygen balance, OC has to match the total oxygen transfer rate (OTR_{tot}) of the system, which is provided by fine bubble (FB) diffusers in the aeration tank and coarse bubbles (CB) in separate membrane tanks. First assessing $OTR_{CB,}$ then closing the balance OC=OTR_{tot} allowed to calculate OTR_{FB} and to fit an exponential relationship between OTR_{FB} and MLSS. A comparison of the α-factor obtained by this balance method and by direct measurements with the off-gas method on the same plant is presented and discussed.

Key words | alpha factor, membrane bioreactor, mixed liquor concentration, oxygen transfer

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INTRODUCTION

One of the key parameters for membrane bioreactor (MBR) design and operation is the air supply (Cornel *et al.* 2003; Krampe & Krauth 2003; Germain *et al.* 2007) and the related energy consumption. In MBRs, aeration is used both for the control of membrane fouling (air scouring with coarse bubble (CB)) and for the oxygen supply to the micro-organisms (process aeration, usually with fine-bubble (FB)). Depending on the oxygen requirements and on the filtration status, the two aeration systems may operate simultaneously or separately, with different air flow rates. The transfer efficiency of FB depends on many factors including air flow rate, F:M ratio, diffuser submergence, … , but the bottleneck parameter in MBRs remains the mixed liquor suspended solids (MLSS) concentration (and the correlated viscosity).

The objective of this paper is to show how daily mass balances (COD and N) performed on full scale MBR plants can be used to calculate the oxygen transfer contribution of each aeration system and estimate the daily average oxygen transfer rate (OTR). The paper focuses on the methodology, and presents results obtained on one full scale MBR plant monitored by Cemagref within the framework of a R&D program of the plant manufacturer. The process was subjected on purpose to large variations of operational parameters, especially sludge concentration. It allowed studying the variations of OTR and of the correlated daily average alpha factor with MLSS concentration.

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MATERIALS AND METHODS

Plant description

The monitored MBR plant (Ultrafor®, Degrémont, France) is located in Grasse in the South-East of France. The plant was designed for 24,000 p.e. with two trains in parallel (Figure 1). The biological reactors (1,000 m^3 in each train, 7 m deep) are equipped with fine bubble diffusers distributed over the entire tank floor. The air flow is provided by dedicated blowers and can be adjusted according to the oxygen requirement. $FeCl_3$ is dosed into the biological reactor for phosphorus removal. Hollow-fibre modules (ZeeWeed 500d, Zenon) are installed in four separate membrane tanks of 65 m^3 each and scoured by coarse bubbles.

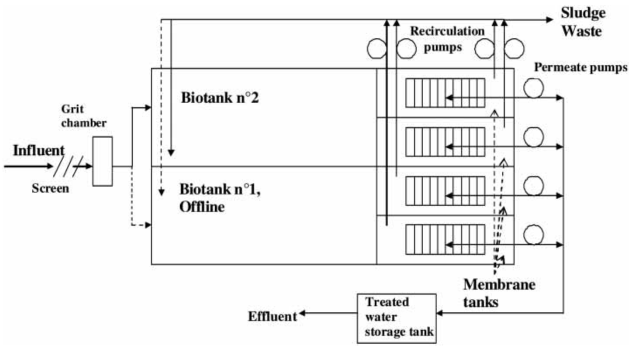

Figure 1 | Layout of the Grasse MBR plant.

The plant was operated in non-standard conditions for R&D purpose. Because the organic loading was about 50% of the design value, one train was shut down for 5 weeks in the summer of 2007 in order to operate the remaining train at its design loading. Nevertheless, three or all four membrane tanks were kept in operation, which increased the ratio of coarse bubble to fine bubble airflow beyond the regular operating range (Table 1). Due to the low hydraulic loading, the membrane tanks were operated in a cyclic mode, with one or two 12-min filtration period at the average membrane flux rate of 18 L m^{-2} h^{-1}, followed by a 1-min backwash sequence and a 10- to 30-min relaxation period. The filtration cycles were offset between tanks, to generate a rotating pattern. Depending on the influent flow rate, one to three membrane tanks were in filtration mode simultaneously. During filtration periods, mixed liquor was fed to the membrane tanks, and recycled back to the aeration tank at a higher solids concentration due to the filtration effect. During relaxation periods, which represented 10 to 12 h day^{-1} per membrane tank, the membrane tanks were operating in batch mode. Air scouring was kept on even during relaxation periods, resulting in quasi-continuous aeration in the membrane tanks (Table 1), and contributing to the total oxygen transfer to the system (Figure 2).

Table 1 | Operating conditions during the monitoring period

		Period 1	Period 2 Period 2a	Period 2b	Period 2c	Period 3
Duration	day	9	5	5	5	10
Influent load						
COD	kg day^{-1}	1,165	1,179	1,284	1,263	1,217
Aeration tank						
Temperature	°C	23.8	24.6	24.9	25.6	26.0
MLSS	g L^{-1}	5.7	6.8	6.7	6.9	8.4
Instantaneous airflow	Nm^3 h^{-1}	1,709	1,731	1,728	1,665	1,730
Air-on time	h day^{-1}	9.1	9.3	9.2	15.4	14.1
Daily airflow	Nm^3 day^{-1}	15,560	16,025	15,849	25,701	24,400
Membrane tanks						
MLSS	g L^{-1}	6.9	8.0	8.0	8.2	10.0
# tanks in service	–	3	3	4	4	4
Instantaneous airflow	Nm^3 h^{-1} $tank^{-1}$	702	785	777	772	750
	Nm^3 h^{-1}	2,107	2,354	3,109	3,088	2,998
Air-on time	h day^{-1} $tank^{-1}$	24.0	24.0	24.0	24.0	24.0
Daily airflow	Nm^3 day^{-1}	50,574	56,498	74,605	74,112	71,957
Total biological system						
F:M	kgCOD$(kgMLVSS\ day)^{-1}$	0.22	0.19	0.20	0.20	0.16
SRT	day	16	18	18	18	28
Membrane tanks/total						
Daily airflow	%	76	78	82	74	75
Oxygen tranfer	%	19	23	30	19	27

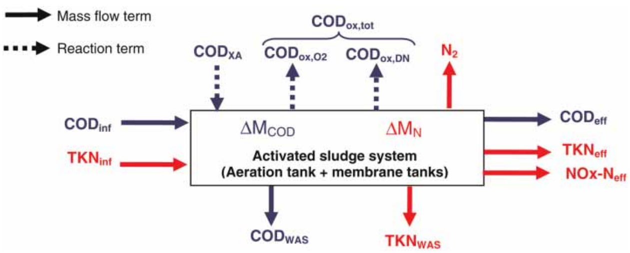

Figure 2 | Mass balance terms for COD and nitrogen.

Data collection

An exhaustive data set was collected from the plant's Supervisory Control And Data Acquisition (SCADA) system, and from additional online sensors and dataloggers installed for R&D purpose (Table 2).

The influent COD and TSS concentrations were monitored with an *in situ* submerged spectrometer (S::CAN Messtechnik, Austria) installed after the screen and calibrated with grab samples. The daily COD and TSS mass flows calculated from sensor data were validated with 24-h composite samples collected once a week. The daily TKN mass flow was calculated from the COD mass flow assuming a constant COD:N ratio over one week. It was an acceptable assumption given the stability of the influent characteristics (Table 1).

Plant operating conditions

The main operating conditions during the 5-week monitoring period are summarised in Table 1. The influent COD load was quite stable during the study; however MLSS and air inputs varied strongly (Table 1). Three main periods can be distinguished based on MLSS (Figure 3). During period 1, the MLSS concentration was increased gradually from 5.0 to 6.8 g L^{-1} by reducing the sludge wastage rate. During period 2, MLSS was stabilized around 6.9 g L^{-1}. During period 3, the MLSS concentration increased linearly up to 9.8 g L^{-1}, because sludge wastage was stopped. As a consequence, the sludge retention time (SRT) increased gradually throughout the monitoring period, from 14 to 32 days.

Period 2 was further subdivided into 3 periods to account for other major operational changes. The plant was initially operated with 3 membrane tanks, but the fourth membrane tank was taken back online after 2 weeks (beginning of period 2b). As a consequence the total airflow and the total sludge mass in the membrane tanks suddenly increased.

Process aeration was initially operated intermittently based on a DO threshold. The resulting daily aeration time remained within a tight range (8.9–9.8 h day^{-1}), which confirms the stable loading rate. Following a sensor failure at the beginning of period 2c, the aeration control was switched to a semi-timer mode leading to an aeration time of approximately 15 h day^{-1}.

Oxygen demand calculations

The daily oxygen consumption of the whole plant was calculated using non-steady state mass balances for COD and total nitrogen (TN) on a 24-h basis (Figure 2). The equations are adapted from steady-state balancing (Barker & Dold 1995; Nowak *et al.* 1999; Metcalf *et al.* 2003, Racault & Gillot 2007) by adding a mass variation term. The total oxygen consumption (OC_{tot}) is the sum of the oxygen used for COD oxidation under aerobic conditions (OC_{COD}) and for nitrification (OC_{Nox}). OC_{COD} is the difference between

Table 2 | Data collected at the plant

	Plant SCADA	R&D measurements On-line	24 h composite samples	Calculations
Inlet	Flow rate	COD, TSS	COD, BOD_5, TSS, TKN, TP	Mass flows: COD, BOD_5, TSS, TKN, TP Ratios: COD:N, COD:BOD_5
Aeration and membrane tanks	Blowers and pump operation	MLSS, DO, temperature Air flow rates	MLVSS	MLVSS mass in tanks
Outlet	Flow rate		COD, NH_4-N, NOx-N, TP	Mass flows: COD, TKN, NH_4-N, NOx-N

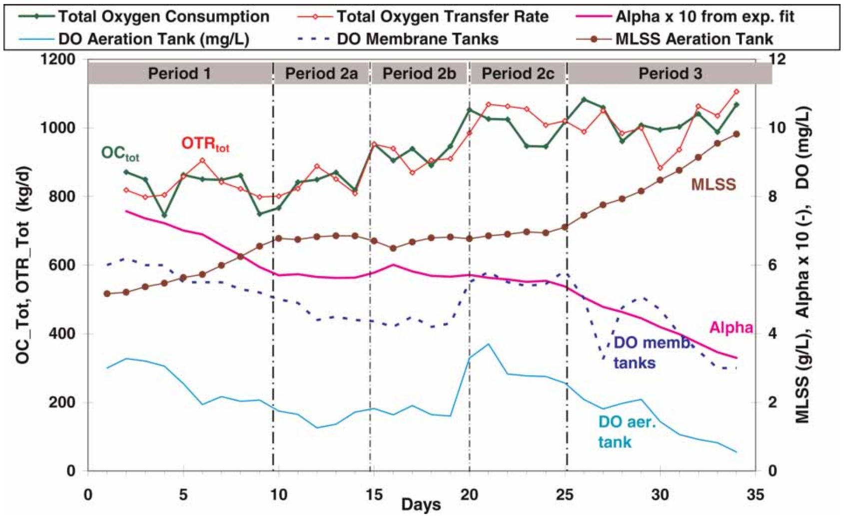

Figure 3 | Daily oxygen concentration and oxygen mass balance results over the whole monitoring period.

the total COD oxidized ($COD_{ox,tot}$) and the COD used for denitrification ($COD_{ox,DN}$).

$$OC_{tot} = OC_{COD} + OC_N = COD_{ox,tot} - COD_{ox,DN} + OC_{Nox}\ [kg\ O_2 day^{-1}] \quad (1)$$

On a 24-h period, the COD mass variation in the whole system (ΔM_{COD}) is written as follows:

$$\Delta M_{COD} = COD_{inf} - COD_{eff} - COD_{WAS} + COD_{XA} - COD_{ox,tot}\ [kg\ COD\ day^{-1}] \quad (2)$$

COD_{XA} corresponds to the COD introduced into the system by the growth of autotrophic nitrifying bacteria using carbon dioxide as the carbon source (Nowak *et al.* 1999). It is proportional to the mass flow of nitrogen oxidised (N_{OX}) according to Equation (3). The nitrified and denitrified mass flows (N_{OX} and N_{DN}) are obtained from a daily non-steady state mass balance on nitrogen (Figure 2).

$$COD_{XA} = Y_A N_{ox} \text{ where } Y_A = 0.24\,g\ COD(g\,N_{OX})^{-1} \quad (3)$$

The daily sludge production (SP_{MLSS}) was calculated by adding the measured wastage from the membrane tanks and the total sludge mass variations in the system. The cumulated plot of sludge production versus COD influent load (not shown) allows extracting a stable sludge production yield (Y_{SP}) for each of the two main ranges of SRT: 0.39 $kgMLSS.(kgCOD)^{-1}$ for period 1+2, and 0.33 $kgMLSS.(kgCOD)^{-1}$ for period 3. When converted to COD, the daily sludge production (SP_{COD}) is expressed as:

$$SP_{COD} = COD_{WAS} + \Delta M_{COD} = (COD{:}VSS).(VSS{:}TSS).Y_{SP}.CODinf\ [kg\ COD\ day^{-1}] \quad (4)$$

The COD:VSS ratio measured on the Grasse sludge (1.41) is in agreement with the literature values (Henze *et al.* 1995).

The final daily oxygen consumption is obtained by combining Equation (1) through (4):

$$OC_{tot} = COD_{inf} - COD_{eff} - SP_{COD} + Y_A N_{ox} - 2.86.N_{DN} + (4.57 - Y_A).N_{ox}\ [kg\ O_2 day^{-1}] \quad (5)$$

Oxygen transfer calculations

The whole system has to be accounted for to calculate the total oxygen transferred (OTR_{tot}), i.e., the OTR in the biological reactor provided by fine bubble (OTR_{FB}) and the OTR in each membrane tank provided by coarse bubble (OTR_{CB}). To initiate the calculation, the mass-transfer coefficient of coarse bubble under process conditions corrected to 20 °C ($k_L a_{CB,f,20}$) was determined from selected re-aeration DO curves recorded in one membrane tank. Since the conditions were not ideal, this approach only delivered a range for the OTR_{CB} value.

The key point of the method is that, to close the oxygen balance, the total oxygen transferred under process conditions must match the total consumption ($OTR_{tot} = OC_{tot}$). So, if OTR_{CB} and OC_{tot} are known, OTR_{FB} can be calculated by difference ($OTR_{FB} = OC_{tot} - OTR_{CB}$). In a first step, this was applied to period 2a + 2b, when airflow and MLSS in the biological reactor were stable. Since it is assumed that $k_La_{FB,f,20}$ only depends on MLSS for a given airflow rate, its value should be constant during those 10 days. $k_La_{FB,f,20}$ was determined for five $k_La_{CB,f,20}$ values sampled within the possible range, by minimizing the difference between the 10-d sums of OC_{tot} and OTR_{CB}. The most likely couple ($k_La_{FB,f,20}$, $k_La_{CB,f,20}$) at MLSS = 6.9 g L^{-1} was then selected using expert judgement.

It was then assumed that unlike for fine bubble aeration, the mass transfer coefficient for coarse bubble aeration was about constant in the MLSS range of the monitoring period. A unique $k_La_{CB,f,20}$ was thus applied for the calculation of the daily average oxygen transfer rate at the sludge temperature T ($OTR_{CB,T}$) for the whole period:

$$OTR_{CB,T} = 1.024^{(T-20)} k_La_{,CB,f,20}(C^*_{\infty f} - C).V_{M.}.n\ [\text{kg } O_2 \text{ day}^{-1}]. \tag{6}$$

Where: $C^*_{\infty f}$: DO concentration at saturation at temperature T in sludge (mg L^{-1}); C : daily average DO concentration (mg L^{-1}); V_M : volume of one membrane tank (m^3); n: number of membrane tanks in operation.

Knowing the total daily air flow rate in membrane tanks, the standard oxygen transfer efficiency under process conditions $\alpha SOTE_{CB}$ (at C = 0 mg L^{-1}, T = 20 °C, per unit depth) can be calculated as well, to verify the consistency and likelihood of the $k_La_{CB,f,20}$ value:

$$\alpha SOTE_{CB} = \frac{k_La_{CB,f,20}.C^*_{\infty f,20}.V_M.n}{0,299.Q_{CB}.d_{CB}}.100\,(\%m^{-1}) \tag{7}$$

where: $C^*_{\infty f,20}$: DO concentration at saturation at 20 °C in sludge (mg L^{-1}); d_{CB} = membrane aerator nozzle depth (m); Q_{CB} = total CB air flow rate (N m^3 h^{-1})

Finally, OTR_{FB} and hence $k_La_{FB,f,20}$ can be calculated for each day from the known OTR_{CB} values by closing the oxygen balance on the whole 5-week monitoring period.

Oxygen transfer measurements

The fine bubble standard OTR in clean water ($SOTR_{FB}$) was measured in biological reactor no. 1 (identical to reactor no. 2) while it was offline, for two air flow rates (Q_{FB}) that are representative of typical operation with sludge. A linear relationship between $SOTR_{FB}$ and Q_{FB} was fitted on the two data points. This allows the calculation of an average alpha factor (α_{FB}) for FB for each $k_La_{FB,f,20}$ obtained from the mass balance method, and thus to study the daily variations of this daily average alpha factor versus MLSS.

Immediately after the monitoring period was over, oxygen transfer performance tests were carried out under process conditions on biological reactor no. 2 using the off-gas method (ASCE 1997; Capela et al. 2004). Four tests were conducted at three MLSS concentrations by transferring sludge to reactor no. 1. The results are compared to the OTR_{FB} obtained from the mass balance method.

RESULTS

The first coarse bubble oxygen transfer assessment was conducted based on reaeration DO curves. This method is not easy to perform in membrane tanks and may give inaccurate results depending of the status of sludge at the beginning of reaeration (Capela et al. 2004). However, after eliminating outliers, most results converged to an average $k_La_{CB,f,20}$ value of 10 h^{-1}. After the second assessment, that consisted in closing daily oxygen balances during period 2a + 2b (constant MLSS) and optimizing k_La values of both aeration systems, the final value selected for $k_La_{CB,f,20}$ was 10.9 h^{-1}. This corresponds to an $\alpha SOTE_{CB}$ of 0.97% m^{-1} at 6.9 gMLSS L^{-1}. This is consistent with $\alpha SOTE_{CB}$ values reported in literature for coarse bubble in MBR, and with results obtained by Cemagref (not published) on other MBR full scale plants.

To calculate the oxygen provided by coarse bubble over any 24-h period, the membrane tanks are considered as aeration tanks integrated into the whole system, where biological activity takes place. Oxygen demand increases during filtration periods (due to feed with fresh activated sludge), and decreases during relaxation periods (batch), when oxygen uptake is mainly due to endogenous respiration. The average OTR_{CB} is calculated from the $k_La_{CB,f,20}$ value and the average daily DO concentration.

Using this OTR_{CB} and closing the oxygen balance allows to calculate a daily OTR_{FB} value on all 3 periods (Figure 3). After correcting OTR_{FB} for temperature and dividing by the results of clean water tests, a 24-h average value of α-factor is obtained for each day. When plotting average α-factor values

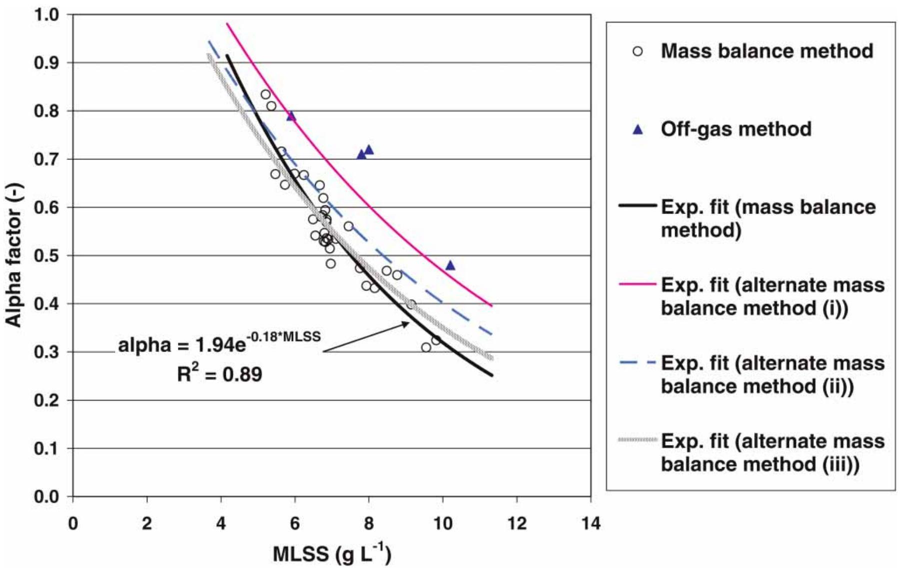

Figure 4 | Alpha factor versus MLSS concentration in the bioreactor obtained by different methods.

versus aeration tank MLSS concentration (Figure 4), an exponential trend can be fitted that yields $Alpha_{FB} = 1.94\ e^{(-0.18\ MLSS)}$. This curve shows a strong decrease of oxygen transfer as the MLSS increases. At 8–10 gMLSS L^{-1}, the alpha factor values appear lower than those reported in literature (Cornel *et al.* 2003; Germain *et al.* 2007), which are themselves lower than those of the off-gas tests carried out on the biological reactor no. 2. Nevertheless, the strong impact of MLSS concentration on alpha is confirmed by measured DO levels in the aeration tank: even though the loading and air flows remained stable during period 3, the average DO decreased strongly at MLSS concentrations above 8.5 g L^{-1} (Figure 3), and DO remained near zero for several consecutive hours during daytime.

DISCUSSION

As mentioned above, the ratio of the coarse bubble air flow to the total airflow was exceptionally high (74–82%, Table 1) during the monitoring period due to R&D experiments. During periods 1 and 2, the high DO concentrations in the membrane tanks (Figure 3) resulted into a lower $OTR_{CB.}$ The 3 membrane tanks initially in service were contributing around 20% of the total OTR (Table 1). The ratio increased to 30% once the fourth membrane tank was brought back online (period 2b). After the dramatic increase of the daily aeration time in the aeration tank (period 2c), the contribution of the four membrane tanks dropped back to 20%.

During period 3, the average DO in all tanks decreased. As a consequence, the OTR in the membrane tanks increased and reached 35% of the total OTR at the end of the period. These variations of OTR_{CB} with DO have a significant impact on OTR_{FB} determined by difference. Given the discrepancy with the results from the off-gas method, it can be questioned if the mass balance method overestimated OTR_{CB} and thus underestimated OTR_{FB} at high MLSS concentrations. To assess the sensitivity of OTR_{CB} on alpha factor, three alternate mass balance methods that yield lower OTR_{CB} were tested (Figure 4):

(i) The contribution of the membrane tanks to OTR_{tot} was limited to the oxygen mass flow recycled with the sludge to the aeration tank. OTR_{CB} then becomes insignificant at the end of period 3, and the FB aeration essentially covers the entire oxygen demand. The daily average alpha factor obtained with this method, that obviously underestimates OTR_{CB} since the oxygen consumption is considered nil in the membrane tanks, is close to the results from the off-gas method (0.48 at 10.2 gMLSS L^{-1}).

(ii) In a second approach, the oxygen used for respiration during the periods when the membrane tanks are isolated (relaxation) was added to the OTR_{CB} obtained above. This offsets the alpha curve by approximately −0.06 at 10 gMLSS L^{-1}.

(iii) In a last approach, it was hypothesized that $k_La_{CB,f,20}$ depends on MLSS as assumed by Verrecht (2008), using the same relationship as for FB. The new alpha curve slightly pivots around the fixed point at 6.9 g L^{-1}, but the increase in alpha values for high sludge concentrations is limited.

The level of confidence in the calculated OC is high, because there is evidence for the reliability of the involved data (influent loads, sludge production). It thus appears that the average alpha factor values obtained by the daily mass balance method cannot be compared to the values from the off-gas method. In the latter method, the transfer is measured under more ideal conditions, with DO being maintained several hours between 1.5 and 4 mg L^{-1}.

CONCLUSIONS AND FUTURE RESEARCH NEEDS

A non steady state mass balance approach is proposed to estimate OTR at full scale under actual operating conditions. It was applied to a MBR plant for a range of MLSS concentrations [5–10 g L^{-1}], allowing extracting a relationship between daily average alpha factor and MLSS. The results (e.g. alpha = 0.32 at MLSS = 10 g L^{-1}) are significantly lower than those obtained by the off-gas method or proposed in the literature. To clarify air supply design and operation guidelines at high MLSS, further research is now required to:

(i) compare the results from the Grasse plant with other full scale MBRs, which is not possible for now due to lack of appropriate data sets;
(ii) understand the difference between the oxygen transfer capacity during regular operating conditions and during off-gas testing conditions;
(iii) investigate how oxygen transfer of coarse bubbles is affected by high MLSS.

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REFERENCES

American Society of Civil Engineers (ASCE) 1997 *Standard Guidelines for In-Process Oxygen Transfer Testing*. American Society of Civil Engineers, New York, NY, USA.

Barker, P. S. & Dold, P. 1995 COD and nitrogen mass balances in activated sludge systems. *Water Research* **29** (2), 633–643.

Capela, S., Gillot, S. & Héduit, A. 2004 Comparison of oxygen-transfer measurement methods under process conditions. *Water Environment Research* **76** (2), 183–188.

Cornel, P., Wagner, M. & Krause, S. 2003 Investigation of oxygen transfer rates in full scale membrane bioreactors. *Water Science and Technology* **47** (11), 313–319.

Germain, E., Nelles, F., Drews, A., Pearce, P., Kraume, M., Reid, E., Judd, S. J. & Stephenson, T. 2007 Biomass effects on oxygen transfer in membrane bioreactors. *Water Research* **41** (5), 1038–1044.

Henze, M., Harremoës, P., La Cour Jansen, J. & Arvin, E. 1995 *Wastewater Treatment: Biological and Chemical Processeses*. Springer-Verlag Berlin Heidelberg, New York.

Krampe, J. & Krauth, K. 2003 Oxygen transfer into activated sludge with high MLSS concentrations. *Water Science and Technology* **47** (11), 297–303.

Metcalf and Eddy, Tchobanoglous, G., Burton, F. L. & Stensel, H. D. 2003 *Wastewater and Reuse*, 3rd edition. McGraw-Hill, New York.

Nowak, O., Frantz, A., Svardal, K., Müller, V. & Kühn, V. 1999 Parameter estimation for activated sludge models with the help of mass balances. *Water Science and Technology* **39** (4), 113–120.

Racault, Y. & Gillot, S. 2007 Use of mass balances for the determination of oxygen contribution of the different air sources in a full-scale membrane bioreactor. In *Proceedings of the 80th Annual Technical Exhibition and Conference (WEFTEC.07), 13–17 October 2007, San Diego, CA, USA*, pp. 3393–3406.

Verrecht, B., Judd, S., Guglielmi, G., Brepols, C. & Mulder, J.W. 2008 An aeration energy model for an immersed membrane bioreactor. *Water Research* **42** (19), 4761–4770.