Investigation of oxygen transfer rates in full scale membrane bioreactors

P. Cornel, M. Wagner and S. Krause

Darmstadt University of Technology, Institute WAR, Wastewater Technology, Petersenstr. 13, 64287 Darmstadt, Germany (E-mail: *p.cornel@iwar.tu-darmstadt.de*)

Abstract In membrane bioreactors (MBRs) for wastewater treatment the secondary clarifier is replaced by a membrane filtration. The advantage of this process is a complete removal of solids from the effluent and a small footprint due to possible high biomass concentrations (MLSS). As oxygen supply counts for more than 70% of total energy cost in municipal WWTPs the design of the aeration system is vital for efficient operation. In this respect the α-value is an important influencing factor. The α-value depends on the MLSS-concentration as shown in various publications and confirmed by own measurements in two full scale municipal MBRs with MLSS ranging from 7 and 17 kg/m^3. Furthermore it must be taken into account that α-values are not static values; they vary with loading rates, surfactant concentrations, air flow rates, MLSS concentrations, etc. The average α-value at typical 12 kg/m^3 MLSS for municipal MBRs is about 0.6 ± 0.1. As submerged configured MBRs are equipped with an additional coarse bubble "crossflow" aeration system for fouling control, supplementary energy is consumed. Therefore MBRs need more energy compared to conventional treatment plants. Measurements of both aeration systems show that the fine bubble aeration system is more efficient by a factor of three concerning oxygen supply compared to the coarse bubble system.

Keywords α-values; membrane bioreactors (MBRs); oxygen transfer rates (OTR)

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Introduction

Membrane bioreactors (MBRs) offer the advantages of a small footprint due to high biomass concentration and a complete removal of solids from the effluent. In Germany two municipal full scale MBRs are in operation; several plants are in planning or under construction. In submerged configured MBRs two different aeration systems are in use. 1. Fine bubble aeration for oxygen supply. 2. Coarse bubble "crossflow" aeration to achieve fouling control at the membrane surface. The necessary shear velocity is produced by the movement of the bubbles close to the membrane surface. A further two different configurations of the membranes are realised: submerged inside the aeration tank (MBR #1) or external in an extra filtration tank (MBR #2). Figure 1 depicts both configurations.

Presently the high energy costs for aeration and to maintain the "crossflow" describe the disadvantages. The coupling of both aeration systems could find a remedy.

Therefore the oxygen transfer rates (OTR) in two full scale municipal immerged configured MBRs were measured in order to determine the OTR of the fine-bubble aeration and of the coarse bubble "crossflow" aeration at different MLSS respectively.

Fundamentals of oxygen transfer tests

The oxygen transfer rate (OTR in kg/h) describes how much oxygen (kg) is dissolved per hour in clean water (or in mixed liquor) at 0 mg/l dissolved oxygen (DO).

For measurement of OTR several methods can be taken in account:

- Non stationary methods (absorption or desorption)
- Stationary method (off gas method)

The change of DO using non stationary methods is described as (Eq. (1)):

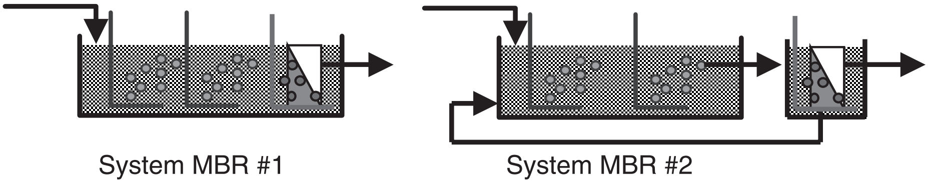

Figure 1 Possible configurations of submerged MBRs

$$\frac{\Delta c}{\Delta t} = k_L a_f \cdot (c_\infty{}^* - c) - \mathrm{OUR} \tag{1}$$

where: $c_\infty*$ = DO saturation concentration [mg/L]
c = DO concentration [mg/L]
$k_L a_f$ = apparent volumetric mass transfer coefficient [1/h]
OUR = Oxygen Uptake Rate [$mgO_2/(L \cdot h)$]

Integrating the above from "0" to "t", assuming that conditions remain constant with time, yields (Eq. (2)):

$$c(t) = c_\infty{}^* - (c_\infty{}^* - c_0) \cdot e^{-k_L a_f \cdot t} \ [\mathrm{mg / L}] \tag{2}$$

where: $c(t)$ = DO concentration at time t [mg/L]
c_0 = DO concentration at time zero $t = 0$ [mg/L]
$k_L a_f$ = apparent volumetric mass transfer coefficient [1/h]

The above equation can be used for clean water tests and for measurements in process water. The parameters $k_L a$ (in clean water) or $k_L a_f$ (under process conditions), c_0, $c_\infty*$ (or c_R in mixed liquor) are determined by oxygen transfer tests. Testing in mixed liquor only the DO value in process water at respiration rate (c_R) can be measured. Therefore the OUR has to be measured in order to determine c_R (Eq. (3)):

$$c_\infty{}^* = c_R + \frac{\mathrm{OUR}}{k_L a_f} \ [\mathrm{mg / L}] \tag{3}$$

where: c_R = DO value at steady state in process water at uptake rate R [mg/L]

Thus the measurement of OUR is necessary for application of non-steady state methods.

By knowing DO saturation concentration and $k_L a_f$ ($k_L a$ for clean water) the OTR can be calculated using Eq. (4):

$$\mathrm{OTR} = \frac{k_L a_f \cdot c_\infty{}^* \cdot V}{1{,}000} \ [\mathrm{mg / L}] \tag{4}$$

where: V = volume of the aeration tank [m^3]

In Figure 2 the fundamentals of oxygen transfer tests using non-steady state method (absorption) are depicted.

Another possibility for determination of OTR is the off-gas method. The off-gas technique offers the advantages of differentiation in time and the abandonment of respiration tests. Using this method oxygen transfer capability is estimated by a gas phase mass balance over the aerated volume. Therefore the concentration of oxygen (O_2) and carbon dioxide (CO_2) from the ambient air and from the off-gas is measured. The respiration can be calculated by Eq. (5):

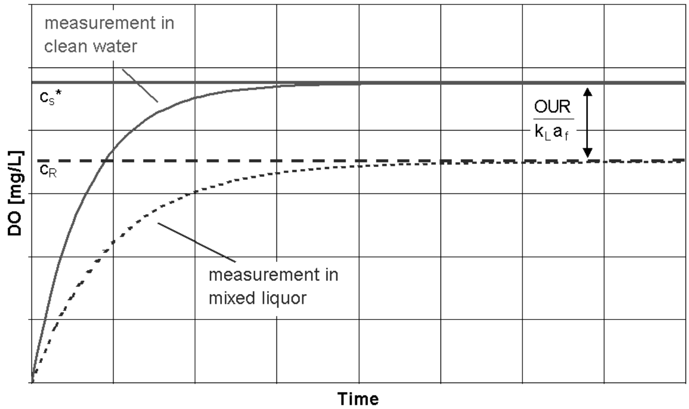

Figure 2 Fundamentals of oxygen transfer tests using non-steady-state methods

$$\mathrm{OUR} = 1{,}000 \cdot \rho_{O2} \cdot \frac{Q_i \cdot Y_i - Q_e \cdot Y_e}{V_H} \; [\mathrm{g/m^3 \cdot h}] \tag{5}$$

where: ρ_{O2} = density of oxygen [kg/m^3]
Q_i, Q_e = inlet (i)/off-gas (e) air flow rate [m^3/h]
Y_i, Y_e = oxygen content inlet air (i), e.g. 20,95% [–], oxygen content off-gas (e) [–]
V_H = volume under hood [m^3]

Oxygen transfer rates on the two existing municipal full scale MBRs in Germany were measured with the non steady state method (absorption method) and with the off-gas method. The tests have been performed in accordance to European Standard pr EN 12255-15 (1999) in clean water and under process conditions at different air flow rates and in mixed liquor at different MLSS concentrations respectively.

Clean water tests in MBRs are performed in the same manner as in conventional activated sludge tanks using the absorption method, whereby the oxygen was depleted by addition of sodium sulfite. Afterwards the increase of the oxygen level is recorded and the aeration coefficient $k_L a_f$ ($k_L a$) can be determined.

As there was no possibility for a refill with clean water between each test and the use of sodium sulfite, the salinity increases and a correction of OTR according to ASCE (2000) had to be calculated (Eq. (6)):

$$\mathrm{OTR}_{1,000} = \mathrm{OTR} \cdot e^{9.65 \cdot \frac{1,000 - \mathrm{TDS}}{100,000}} \; [\mathrm{kg/h}] \tag{6}$$

TDS = Total Dissolved Solids

Under process conditions the oxygen level is decreased by the respiration of the micro-organisms. The subsequent increase of the oxygen level after the aeration has started is measured in the same manner as in clean water. For determination of the OTR the OUR has to be taken into account.

Performing the off-gas method the respiration rate need not be measured. The oxygen concentration of the ambient and off-gas air is measured by an analyser. Further the gas flow (inlet air and off-gas air flow) and the DO has to be measured.

The tests under process conditions in MBRs require additional modifications because of the high biomass concentration. Therefore the oxygen probes must be equipped with a separate stirrer and installed “up side down”. Furthermore the required respiration tests for determination of OUR (absorption method) should be executed full scale (inside the tank). This can only be performed in tanks equipped with mixers.

Results

Figure 3 shows results of the fine-bubble oxygen transfer tests in the municipal full scale MBR #2 (results from non-stationary measurement). Depicted is the volumetric OTR vs. the specific air flow rate. As expected a linear dependency of OTR and air flow rate is given. Furthermore the OTR decreases at increasing MLSS concentrations. In this case at 14 kg/m^3 MLSS and an air flow rate of about 3 m^3/(m^3·h) at standard conditions an OTR of about 100 g/(m^3·h) was determined. At about 10 kg/m^3 MLSS (9.5 and 11 kg/m^3 were measured) an OTR of about 150 g/(m^3·h) was calculated. In clean water the OTR amounts to about 230 g/(m^3·h).

Both methods, non-stationary (absorption method) and stationary off-gas method, result in about the same value of OTR. In evidence the OTR determined by the off-gas method varies, because with this method variations in location and time can be pointed out. The advantage of the off-gas method is an exact record of the OTR and thereby of the α-value.

The α-value is defined as the ratio of the volumetric transfer coefficient under process conditions to the clean water transfer coefficient. By application of the off-gas method under real process conditions the resultant α-values vary in time because of variations of the loading rate and for this reason of surfactants.

Figure 4 depicts as an example the α-value in the full scale MBR #2 during one day of measurement with the off-gas method.

Mean α-values in dependence of MLSS concentration can only be depict in ranges. The ranges in MBR #2 result from the application of the off-gas method. In MBR #1 the ranges are larger because of the clean water tests under different hydraulic conditions (absence of membranes in the clean water tests). Figure 5 depicts the average α-values in dependence of MLSS for the two full scale MBRs. Measurements between 7 and 17 kg/m^3 MLSS concentration were performed. The average α-values in this range are between 0.7 and 0.4 respectively.

As shown in Figure 5 the α-values of both municipal MBRs are in the same order of magnitude. At increasing MLSS concentrations decreasing α-values are determined. At usually 12 kg/m^3 MLSS concentration in submerged configured MBRs the average α-value of both treatment plants is about 0.6 ± 0.1. Considering the high sludge ages of 30–40 days, this value might be about 0.2 units lower compared to conventional stabilization plants at 3–5 kg/m^3 MLSS concentration, where α-values of about 0.8 are reported

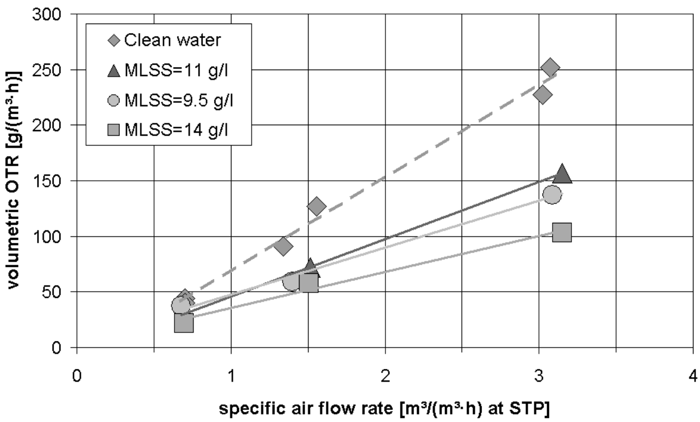

Figure 3 OTR at different biomass concentrations in MBR #2 (standard conditions)

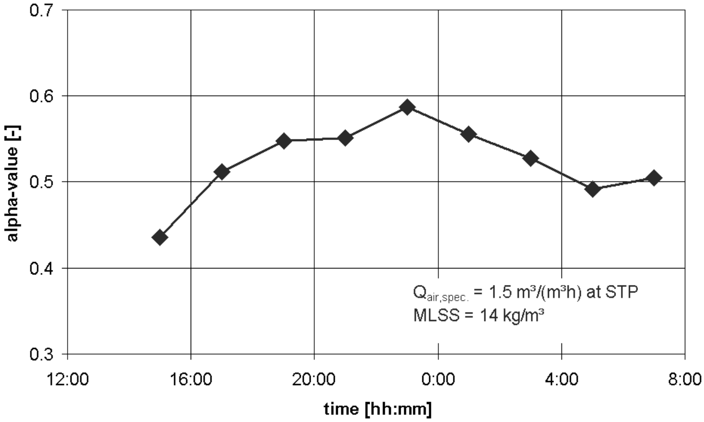

Figure 4 α-values against time at MBR #2

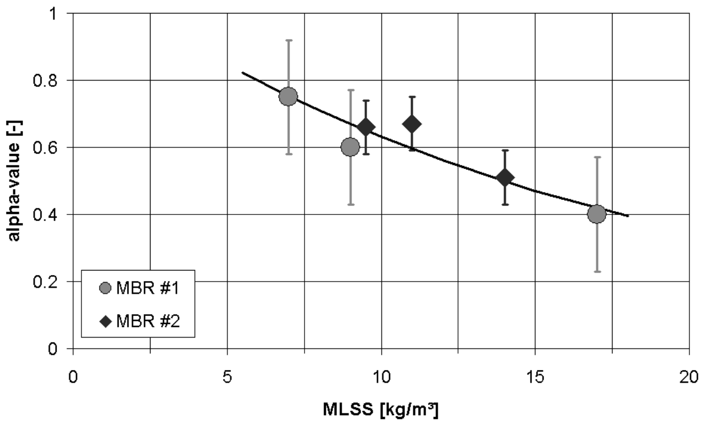

Figure 5 α-values against MLSS concentration in full scale MBRs

(Wagner, 2001). In MBRs the sludge age is about 30–40 days and therefore a comparison with treatment plants which apply aerobic stabilization has to be done.

Oxygen transfer tests at the additional "crossflow" aeration which acts as the source of scour at the membrane surface were performed. In order to generate a high liquid shear velocity the air flow rate from this aeration system is more than twice the value compared to the fine bubble aeration system. For comparison Figure 6 shows the volumetric OTR of both aeration systems in the full scale MBR #2. Depicted is the volumetric OTR in dependence of the specific air flow rate.

In evidence the OTR of the fine bubble aeration is much higher at less air flow. Otherwise, as a positive side effect, the "crossflow" aeration is able to supply additional oxygen.

The specific aeration efficiency (SAE) indicates an energy consumption of the "crossflow" aeration of about three times the value of the fine bubble aeration (Figure 7). At MLSS of 7 kg/m^3 an SAE of 0.8 kg/kWh for "crossflow" aeration was determined. For fine bubble aeration the SAE is about 2.4 kg/kWh at a specific air flow of 3 m^3/(m^3·h) at STP.

Therefore the energy consumption of MBRs are higher compared to conventional WWTPs. MBR #1 with membranes configured inside the aerated tank has an energy consumption of about 1 kWh/m^3 compared to the 0.4 kWh/m^3–0.6 kWh/m^3 of conventional WWTPs. MBR #2 equipped with an extra filtration tank consumes about 2.5 kWh/m^3. In this plant the energy for return sludge from the filtration tank to the aerated tank amounts to

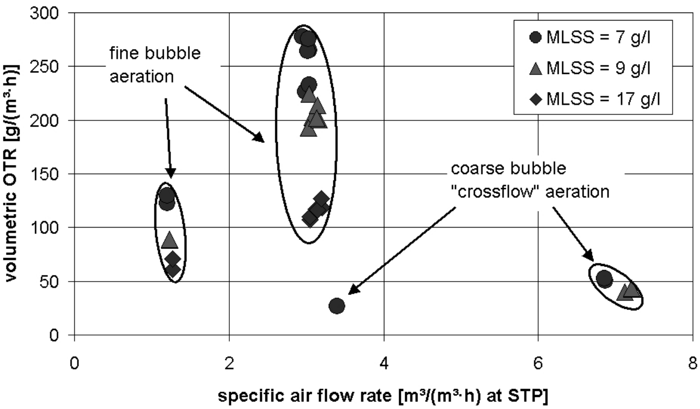

Figure 6 Comparison of volumetric OTR of both aeration systems

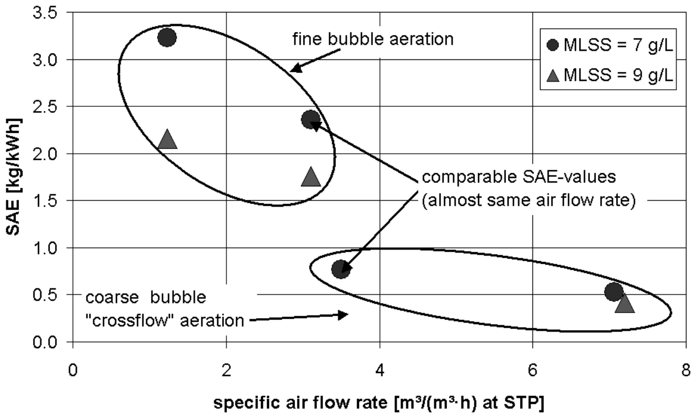

Figure 7 Aeration efficiency of both aeration systems

about 0.44 kWh/m^3. Additionally, 0.84 kWh/m^3 for the "crossflow" aeration are consumed.

Conclusions

Within the scope of the presented investigations aeration tests in full scale municipal MBRs were performed. The results of both MBRs show the same tendencies. The fine bubble aeration system at different MLSSs indicates a dependence of α-value and MLSS. At decreasing MLSSs increasing α-values are observed. The mean α-value in municipal MBRs at usually 12 kg/m^3 MLSS is in the same order of magnitude of 0.6 compared to conventional municipal WWTPs. This corresponds to the usual α-values of conventional WWTPs equipped with fine bubble aeration systems, but this value is about 0.2 units below conventional treatment plants with sludge ages > 25 days.

The aeration tests furthermore pointed out that α-values vary during the day by $\pm$ 0.1, because of variations in the reactor feed. For this reason it's obvious that the α-value is not a constant value. These results were achieved by application of the off-gas method which is, contrary to the absorption method, able to differ in time. Nevertheless both methods result in the same average α-values.

The coarse bubble "crossflow" aeration system indicates no dependence of α-value and MLSS. This may be caused by the lower viscosity as a result of the much higher turbulence caused by the "crossflow" aeration compared to the fine bubble aeration system. The specific air flow rate of the "crossflow" aeration is about 7 $m^3/(m^3 \cdot h)$ at standard conditions in MBR #1 and about 60 $m^3/(m^3 \cdot h)$ in MBR #2 compared to 3 $m^3/(m^3 \cdot h)$ of the fine bubble aeration. Anyhow the "crossflow" aeration system is able to supply additional oxygen.

The energy consumption of the "crossflow" aeration system for fouling control is about three times in value compared to the fine bubble aeration system which provides oxygen supply. Therefore the energy consumption of municipal MBRs is higher compared to conventional MBRs. MBR #2 (equipped with an extra external filtration tank) consumes about 2.5 kWh/m^3 and MBR #1 (membranes submerged inside the aeration tank) has an energy consumption of about 1.0 kWh/m^3 compared to 0.4–0.6 kWh/m^3 for conventional municipal WWTPs. The higher amount at MBR #2 results from the external configuration of the submerged membranes in an extra filtration tank.

The measured results regarding the α-value show that MBRs represent an alternative solution to conventional WWTPs in wastewater treatment. The energy consumption for aeration in municipal MBRs is due to the measurements in full scale MBRs of the same magnitude as municipal conventional WWTPs. Anyhow, beside the energy for aeration, the energy for the generation of the crossflow has to be taken in account.

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