Water research vol. 41. no 5. pp1038-104,4 March 2007

Biomass effects on oxygen transfer in membrane bioreactors

E. Germain [a b], F. Nelles [c], A. Drews [c], P. Pearce [d], M. Kraume [c], E. Reid [a], S. J. Judd [a], T. Stephenson [a*]

[a] School of Water Sciences, Cranfield University, MK43 0AL, UK

[b] current address: Thames Water Utilities Ltd., Manor Farm Road, Reading, RG2 0JN, UK

[c] Institut für Verfahrenstechnik, TU Berlin, Sekr. MA 5-7, Straße des 17. Juni 135, D-10623 Berlin, Germany

[d] Thames Water Utilities Ltd., Manor Farm Road, Reading, RG2 0JN, UK

[*]corresponding author. Fax: +44 1234 754035; E-mail address: t.stephenson@cranfield.ac.uk

Abstract

Fine bubble aeration and biomass characteristics were studied for their impact on oxygen transfer in membrane bioreactors (MBRs). Ten biomass samples from both municipal and industrial pilot and full scale submerged MBRs with mixed liquor suspended solids concentrations (MLSS) ranging from 7.2 to 30.2 $g.L^{-1}$ were studied at six air flow rates (0.7, 1.3, 2.3, 3, 4.4 and 6 $m^3.m^{-3}.h^{-1}$). Graphical and statistical analyses were applied to the results to identify the relative impacts of the various bulk biomass characteristics on oxygen transfer, the former being solids concentration, viscosity, particle size distribution, concentrations of COD, protein and carbohydrate in the soluble microbial product, SMP, and in the extracellular polymeric substances, EPS. Of the biomass characteristics studied, only solids concentration (correlated with viscosity), the carbohydrate fraction of the EPS (EPS_c) and the COD concentration of the SMP (SMP_{COD}) were found to affect the oxygen transfer parameters k_La_{20} (the oxygen transfer coefficient) and α-factor. The relative influence on k_La_{20} was MLSS > aeration > EPS_c > SMP_{COD} and on α-factor was MLSS > SMP_{COD} > EPS_c > aeration. Both k_La_{20} and α-factor increased with increasing aeration and EPS_c and decreased with increasing MLSS and SMP_{COD}. MLSS was found to be the main parameter controlling the oxygen transfer.

Key words

Oxygen transfer, MBR, biomass, aeration.

Introduction

Combining membrane technology with biological treatment, the membrane bioreactor (MBR) is an alternative to the conventional activated sludge (CAS) process (Stephenson *et al.*, 2000). The sedimentation stage of the CAS process is replaced by a membrane filtration stage, reducing the footprint significantly and improving effluent quality due to the removal of the suspended and colloidal material (van der Roest *et al.*, 2001). However, high running costs, arising partly from operating membranes at high solids concentrations, restrict the use of MBRs (Hong *et al.*, 2002). The MBR main power requirement comes from aeration, which is used for supply of dissolved oxygen and to maintain solids in suspension. The biological aeration requirements are higher than in conventional activated sludge process due to the lower oxygen transfer rate initiated by highly concentrated biomass (Cornel *et al.*, 2003; Rosenberger, 2003). Additionally, membrane cleaning, in submerged MBRs, is provided by air scouring, and agitation of fibres in the case of hollow fibre membranes (Germain *et al.*, 2005).

As in all aerobic biological systems, biomass contained in the MBR requires oxygen to perform diverse chemical reactions (Germain and Stephenson, 2005). The amount of oxygen diffusing in the mixed liquor is characterised by the oxygen mass transfer coefficient. The main parameter used to characterise the oxygen transfer in aeration processes is the overall mass transfer coefficient, k_La; where k_L represents the mass transfer coefficient based on the liquid film resistance and a, the specific interfacial area. Another parameter commonly used to describe the oxygen transfer in biological aerated systems is the α-*factor* (WEF and ASCE, 2001). This correction factor is defined as the ratio between k_La in the process solution and k_La in clean water. It accounts for the effect of process water characteristics on the oxygen transfer coefficient.

In MBRs, as in all aerobic wastewater processes, both the biomass characteristics and the design of the aeration system affect the oxygen transfer (Mueller *et al.*, 2002). Biomass is a heterogeneous mixture of particles, microorganisms, colloids, organic polymers and cations, of widely varying shapes, sizes and densities. All these parameters impact on oxygen transfer (Germain and Stephenson, 2005). Mass transfer is also linked with contact area size between gas and liquid phases, i.e. bubble shape and solids concentration (Garcia-Ochoa *et al.*, 2000). Bubble characteristics differ depending on the kind of aerator used and the bubble coalescence effect created by the biomass characteristics (Germain and Stephenson, 2005). The aeration in MBRs is generally provided by fine bubble aerators, used to keep the content of the aerobic tank well mixed and provide oxygen to the biomass. In addition, in submerged MBRs, coarse bubble aerators situated under the membrane modules are used to scour and/or gently agitate the membranes in order to control membrane fouling (Stephenson *et al.*, 2000).

For a better understanding of the phenomena occuring in aerated MBR biomass, closer investigations of each of its characteristics are needed to improve the aeration efficiency and so reduce the operating costs. Until now, such investigations have been generally limited to impacts of solids concentration and viscosity. Other biomass characteristics worth considering include soluble microbial products (SMP) and extracellular polymer substances (EPS); both mainly of microbial origin (Wingeder *et al.*, 1999). The SMP is ostensibly soluble and is part of the liquid phase, whereas EPS is bounded to the cells and thus is part of the solid phase. A comprehensive study of the effects of MBR sludge characteristics on oxygen transfer has been carried out on sludges from several full and pilot scale municipal and industrial MBRs using a bubble column. The use of the same experimental set-up to perform oxygen transfer tests on biomass taken from different MBRs has allowed a direct comparison of the effect of the biomass characteristics and airflow rates on the oxygen transfer without the added effects of the different plant designs such as tank geometry and hydrodynamics.

Material and methods

Oxygen transfer coefficient, k_La, and α-factor determinations

The non steady-state batch test under endogenous respiration conditions and with no recycle flow described by WEF and ASCE (2001) was used to determine the k_La of the biomass samples. Oxygen transfer tests were performed in a 0.02 m^3 working volume bubble column of 2.5m in height and 10 cm in diameter. The fine bubble diffuser was a single *Sanitaire* ceramic disc with a 6 cm diameter. The column was filled with biomass and the airflow was turned off until the DO concentration reached 0.8 $mg.L^{-1}$ or below and then adjusted to a specific airflow rate. The air came from the air compressed line of Cranfield University pilot hall. The airflow rate was corrected for the impact of the liquid head pressure and was normalised at atmospheric pressure. The dissolved oxygen (DO) concentration was monitored using a DO probe (*OxyGuard*) connected to a combined meter and data logger (*OxyLog*). The DO probe was located 1 m above the diffuser at a 45^o angle in order to have a steady current on the probe membrane. DO concentration and temperature were recorded until the DO concentration reached its saturation value. The software (*OxyLog*) was used to download the data on a computer (*Partech Instruments*, St Austell, UK).

Ten biomass samples of 25 L were collected from seven different submerged MBRs (Table 1). The two pilot-scale and the five full-scale plants all treated municipal wastewater except for Plant B, which treated both municipal and dairy wastewater. The plants were operated with either *Zenon* hollow fibres membranes or *Kubota* flat sheet membranes. The samples were transported in containers to Cranfield University Sewage Treatment Works Pilot Hall, transport times being less than 24h at all times. A homogeneous biomass sample of approximately 300 mL was taken from each container before carrying out the oxygen transfer experiments. The biomass characteristics of the sample were then determined in the laboratory.

The non-linear regression method was used to determine k_La and the steady state dissolved oxygen saturation concentration, $C^*_{\infty f}$. (SPSS 11.0, SPSS UK Ltd., UK). The oxygen transfer coefficient values, k_La_f, were standardised at a temperature of 20^oC and are referred as k_La_{20} in this paper. The α-factor was calculated as the ratio of k_La_{20} in the biomass to k_La_{20} in clean water.

Analytical methods

Particle size distributions were determined by laser diffraction using a *Malvern Mastersizer 2000* (*Malvern Instruments Ltd*., Malvern, UK) and reported as the mass median diameter (MMD) (Houghton and Stephenson, 2000). Viscosity was analysed at shear rates from 0.4 s^{-1} to 22 s^{-1} in a *DV-E Brookfield* digital viscometer (*Brookfield*

Viscometers Ltd, Harlow, UK). Viscosity in this paper is quoted at a shear rate of 12.24 s^{-1}. The SMP were extracted by centrifuging the biomass for 5 min at 5000 rpm (Rotanta 96R, Hettich-Zentrifugen, Tuttlingen, Germany) and the supernatant was filtered through 0.2 μm glass fibre filters (GF 52, Schleicher & Schuell, London, UK). The EPS were extracted following the heating procedure of Zhang *et al.* (1999). Protein and carbohydrate concentrations were determined by UV absorbance on a UV/visible spectrophotometer (Model 6505 S, Jenway, Dunmow, UK) with reference to bovine serum albumin (Sigma, Poole, UK) and glucose standards (Sigma, Poole, UK) respectively. The carbohydrate concentration was determined following the method of Dubois *et al.* (1956). Chemical oxygen demand (COD) was measured using a photometric method (Merck, VWR International Ltd, Poole, UK). Suspended solids were measured according to standard methods (APHA, 1998).

Statistical analysis

Statistical analysis was performed to determine the influence of the biomass characteristics and the airflow rate on the oxygen transfer. The multiple regression analysis was chosen to analyse the relationship between the independent variables (biomass characteristics and aeration) and the dependent variable (oxygen transfer coefficient). Modified or standardised regression coefficients, called *Beta coefficients*, were used to interpret the regression model. They have a common unit of measurement and so allow direct comparison of the impact of each independent variable (Hair *et al.*, 1998). Prior to the multiple regression analysis, the relationships between the biomass characteristics were examined by computing a Pearson product-moment correlation matrix. In case of multicollinearity, the process of determining the contribution of each independent variable would be made more difficult because the effects of the independent variables would be mixed or confounded. If variables are highly correlated to each other, only one of them should be kept to represent this group of variables in the multiple regression analysis. Correlation coefficients, *r*, equal to +1 or –1 represent a perfect positive or negative correlation respectively. A correlation coefficient value of 0 represents a lack of correlation. The data was analysed using *Statistic*a (StatSoft Inc., 2000).

Results

Biomass with MLSS concentrations ranging from 7.2 to 30.2 $g.L^{-1}$ were examined (Table 1). The oxygen transfer characteristics (k_La_{20} and α-factor) were compared with the volumetric airflow rates and MLSS concentrations.

An increase in volumetric airflow rate led to an increase in k_La_{20} (Figure 1), whereas an increase in MLSS concentration resulted in an exponential decrease in k_La_{20} (Figure 2). The k_La_{20} decreased sharply for biomass conditions at MLSS concentrations ranging between 7.2 and 17.9 $g.L^{-1}$. With biomass conditions at MLSS concentrations ≥ 17.9 $g.L^{-1}$, k_La_{20} values were very low; further increases in MLSS concentration did not lead to a significant decrease in k_La_{20}. At very high MLSS concentrations (above 17.9 $g.L^{-1}$) the impact of volumetric airflow rate became insignificant. The biomass conditions with the lowest MLSS concentrations and the highest volumetric airflow rates led to the highest k_La_{20} values, whereas the biomass conditions with the highest MLSS concentrations and the lowest volumetric airflow rates led to the lowest k_La_{20} values, which were sometimes below the limit of detection (Figure 1). Both the biomass characteristics and the volumetric airflow rate were found to have an impact on k_La_{20}.

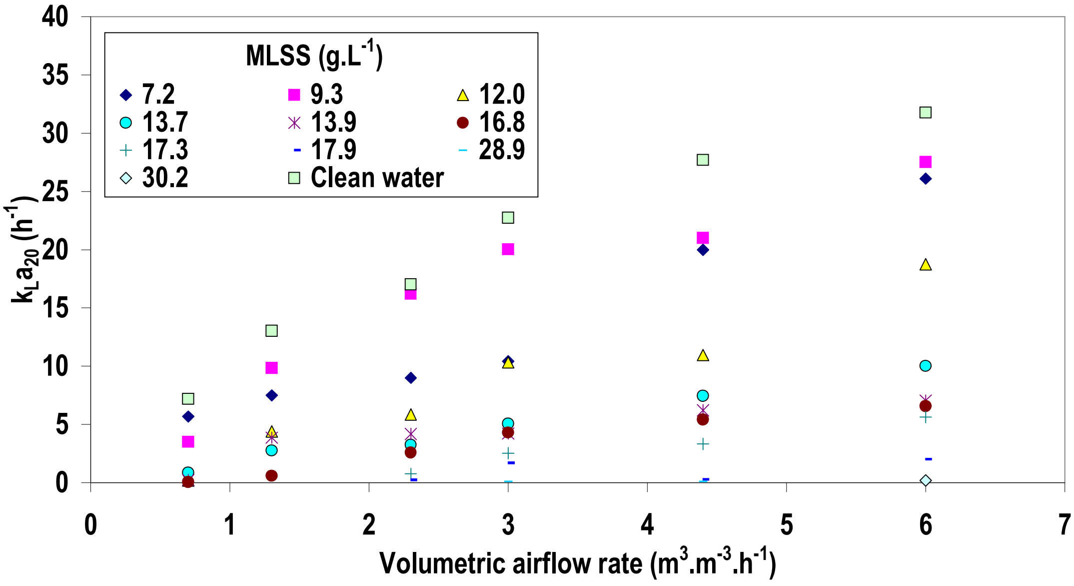

Figure 1. k_La_{20} vs. volumetric airflow rate for the 10 MLSS concentrations studied.

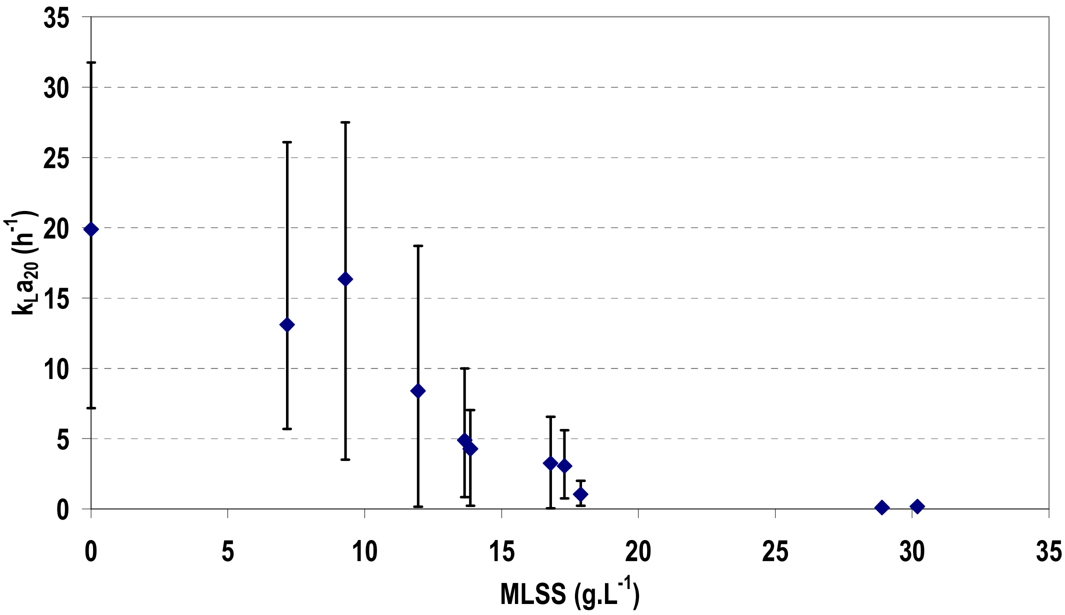

Figure 2. k_La_{20} averaged for all volumetric airflow rates vs. MLSS concentration (mean values and ranges).

Prior to the multiple regression analysis, the biomass characteristics (Table 1) were assessed for linear multicollinearity. The three variables found to be consistently highly correlated to each other (p-level > 0.01 and $r \geq 0.86$) were the MLSS and MLVSS concentrations and the viscosity (Table 2). The variable MLSS was chosen to represent this group of variables in the multiple regression analysis. Due to high correlations between these three variables, their separate effect on the oxygen transfer could not be determined. Any reference to MLSS therefore also applies to MLVSS and viscosity.

The independent variables included in the regression model were the MLSS, EPS_c, EPS_p, EPS_{COD}, SMP_c, SMP_p, SMP_{COD}, MMD and volumetric airflow rate (aeration); the units of the biomass variables were the same as in Table 1 and the aeration variable was in $m^3.m^{-3}.h^{-1}$. The dependent variable was k_La_{20} in h^{-1}. The variables found to have an impact on k_La_{20} were MLSS, EPS_c, SMP_{COD} and aeration (Table 3). According to the *Beta coefficients*, their degrees of influence were, from the greatest to the lowest effect: MLSS > aeration > EPS_c > SMP_{COD}. The MLSS and the SMP_{COD} had a statistically negative influence on k_La_{20}, i.e. an increase in these variables led to a decrease in k_La_{20}, whereas the aeration and the EPS_c had a statistically positive influence on k_La_{20}: an increase in these variables led to an increase in k_La_{20}. However, EPS_p, EPS_{COD}, SMP_c, SMP_p, and MMD were found to have no impact on k_La_{20}.

No particular relationship was observed between the volumetric airflow rate and α-factor (Figure 3), whereas an increase in MLSS concentration led to an exponential decrease in α-factor (Figure 4). The α-factor decreased sharply for biomass conditions with MLSS concentrations up to 17.9 g.L^{-1}. No significant decrease in α-factor was observed for further increases in MLSS concentration.

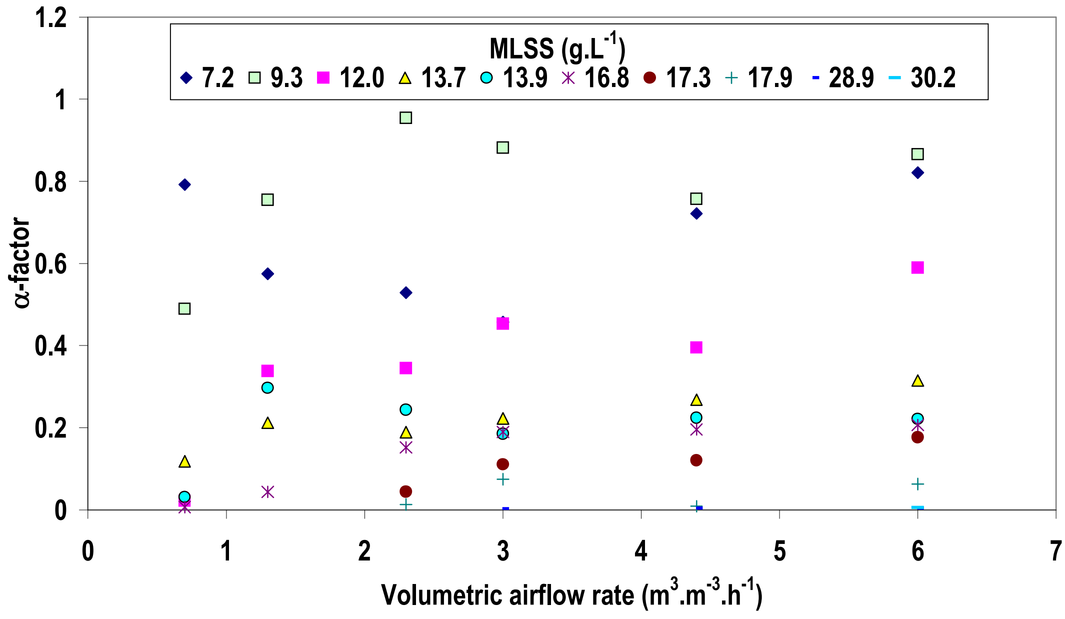

Figure 3. α-factor vs. volumetric airflow rate for the 10 MLSS concentrations studied.

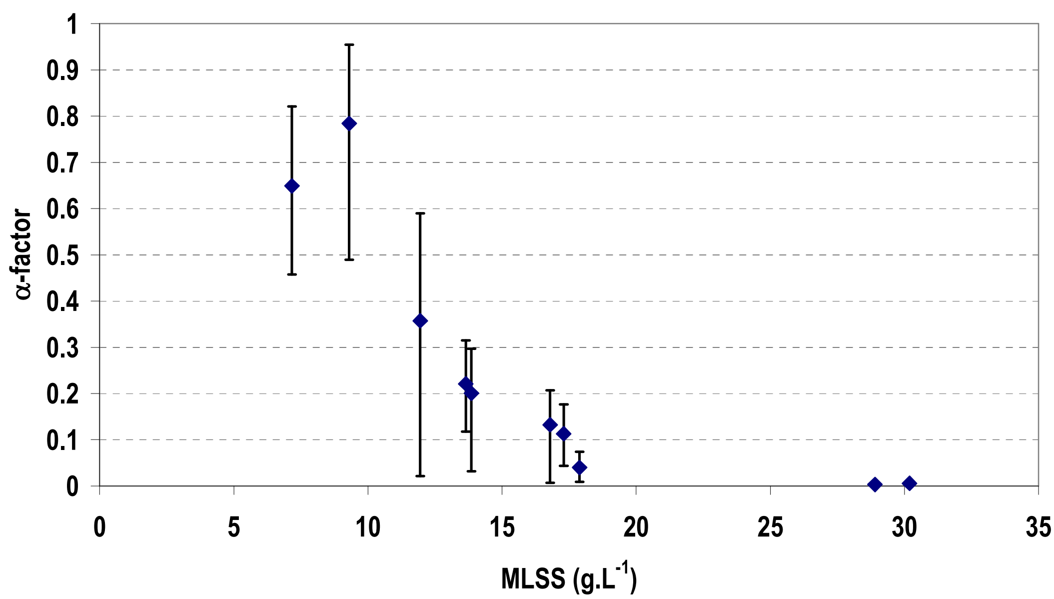

Figure 4. α-factor averaged for all volumetric airflow rates vs. MLSS concentration (mean values and ranges).

The same independent variables as for the k_La_{20} study were entered in the regression models, with α-factor as the dependent variable. The variables found to have an influence on α-factor were, from the greatest to the lowest effect and according to the *Beta coefficients*: MLSS > SMP_{COD} > EPS_c > aeration (Table 4). MLSS and SMP_{COD} had a statistically negative influence on α-factor, i.e. an increase in these variables led to a decrease in α-factor. In contrast, EPS_c and aeration had a statistically positive influence on α-factor: an increase in these variables led to an increase in α-factor. According to the *Beta coefficients* (Table 4) MLSS noticeably had the greatest effect on α-factor. SMP_{COD} and EPS_c exerted almost the same degree of influence with *Beta coefficients* of –0.40 and 0.38 respectively. The impact of aeration on α-factor was significantly lower. The EPS_p, EPS_{COD}, SMP_c, SMP_p, and MMD were not detected as variables having a significant influence on α-factor.

Therefore the same parameters were found to affect k_La_{20} and α-factor: the volumetric airflow rate, the MLSS concentration (and its correlated parameters: MLVSS and viscosity), the SMP_{COD} and the EPS_c. However the EPS_p, EPS_{COD}, SMP_c, SMP_p, and MMD were not detected as parameters having an impact on the oxygen transfer. In summary, both k_La_{20} and α-factor respectively increased with increasing aeration and EPS_c and decreased with increasing in MLSS and SMP_{COD}. Hence, the degrees of influence of the four parameters found to affect the oxygen transfer were not ranked in the same order for k_La_{20} and α-factor. The order of their degrees of influence were for k_La_{20}: MLSS > aeration > EPS_c > SMP_{COD} and for α-factor: MLSS > SMP_{COD} > EPS_c > aeration.

Discussion

Several other studies have also reported an exponential correlation between α-factor and MLSS concentration: Muller *et al.* (1995), Günder (2001), Rosenberger (2003) and Krampe and Krauth (2003). However, the shapes of the exponential curves were slightly different (Figure 5). The different studies were undertaken in tanks of different geometries using dissimilar aeration devices leading to different energy dissipation rates and shear stresses. For the present study, high variations were observed around the mean values (Figure 5), and these variations were related to changes in the volumetric airflow rate. The MLSS concentration was the parameter chosen to represent the biomass characteristics. However, other biomass characteristics, such as EPS and viscosity, affect the oxygen transfer (Krampe and Krauth, 2003); for a defined value of MLSS concentration, some of the other parameters characterising the biomass could have highly different values.

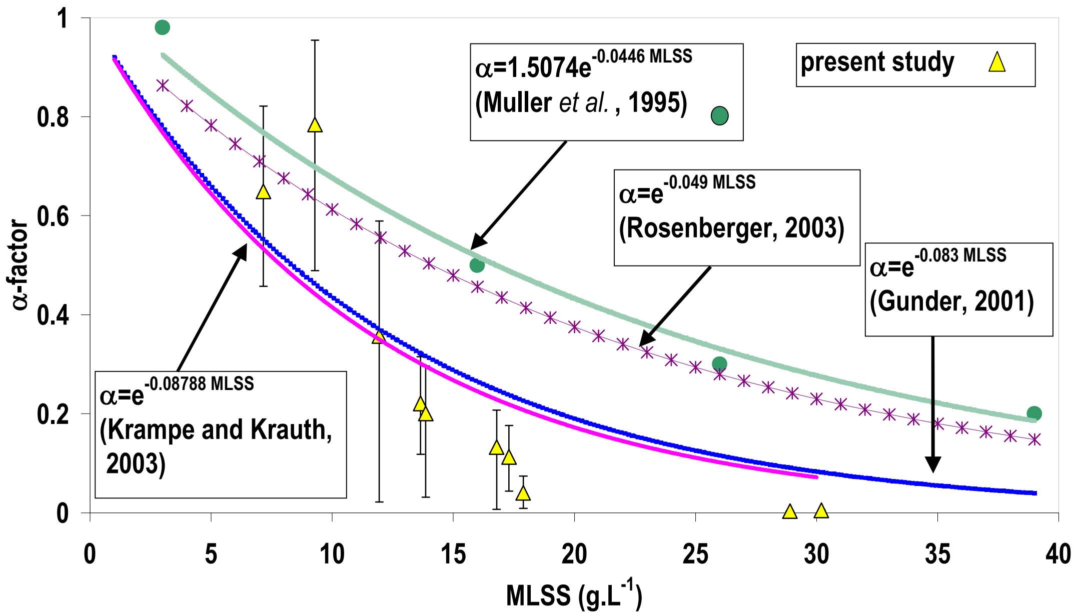

Figure 5. Comparison of the correlations obtained between α-factor and MLSS concentration for several studies (means and ranges showed for the present).

The particle size (represented by the MMD) was expected to be one of the parameters influencing the oxygen transfer, as a change in particle size has been reported to affect the bubble coalescence and therefore the oxygen transfer (Fujie *et al.*, 1992, Ozbek and Gayik, 2001). The method used for particle size measurement (which implied diluting the biomass in water) might have led to results unrepresentative of actual biomass particle size. Moreover, MMD corresponds to the size at which 50% of the sample was smaller and 50% larger, and therefore does not describe the whole range of particle size found in the biomass sample.

MLSS was found to be the main parameter controlling both k_La_{20} and α-factor, corroborating several studies which have established the negative effects of solids concentration on oxygen transfer (Muller *et al.*, 1995; Günder, 2001; Krampe and Krauth, 2003; Van Weert *et al.*, 1995; Ju and Sundararajan, 1994; Freitas and Teixeira, 2001; Verlaan and Tramper, 1987; Ozbek and Gayik, 2001; Rosenberger, 2003). Moreover, the MLSS concentration also accounted for the effects of the viscosity, which has been shown to have a noticeable effect on oxygen transfer (Koide *et al.*, 1992; Özbek and Gayik, 2001; García-Ochoa *et al.*, 2000; Badino *et al.*, 2001; Jin *et al.*, 2001; Rosenberger, 2003). MLSS concentration can easily be controlled in MBRs by adjusting the amount of sludge wasted (Stephenson *et al.*, 2000). Therefore the oxygen transfer can be improved by applying specific operating conditions to keep the MLSS concentration low (below 10-15 $g.L^{-1}$). This relates to diffusivity: in order to be able to reach the active sites of the bacterial cell membrane, the oxygen contained in the air bubbles needs to penetrate the liquid film surrounding the flocs (SMP) and then diffuse through the floc matrix (EPS) (Mueller *et al.*, 2002). The

COD fraction of the SMP was found to have an influence on the oxygen transfer parameters studied but not its carbohydrate and protein fractions. The COD mainly pertains to the organic material in wastewater, which includes proteins and carbohydrates among other compounds. Some of the compounds of the wastewater liquid phase found to have a major impact on the oxygen transfer are surfactants (WEF and ASCE, 2001; Mueller *et al.*, 2002). As surfactants are organic molecules, the COD measurement can be expected to partly account for the surfactants present in the biomass. Surfactants affect the two terms making up k_La, by reducing the liquid film mass transfer coefficient, k_L, and by increasing the surface area, a (Mueller *et al.*, 2002). In the present study, an increase in SMP_{COD} led to a decrease in both k_La_{20} and α-factor, suggesting that the liquid film coefficient was more affected by the SMP_{COD} (part of it corresponding to the surfactants fraction of the liquid phase) than the surface area. The impact of the SMP_{COD} on the oxygen transfer parameters could be explained by the presence of surfactants in the biomass. However, other compounds detected by the COD test and present in the liquid phase of the biomass might have also had an impact on the oxygen transfer. Only the carbohydrate fraction of the EPS was found to have an impact on oxygen transfer. The EPS_c contributes to the fundamental structure of the EPS matrix, facilitating the aggregation of cells and the formation of large flocs (Wingeder *et al.*, 1999). Large flocs possess higher porosities than small ones, corresponding to higher diffusivities (Mueller *et al.*, 2002). The carbohydrate fraction of the EPS was the main EPS fraction influencing oxygen transfer, suggesting that, in the present study, the carbohydrate of the EPS increased floc diffusivity.

Conclusions

- An increase in solids concentration led to an exponential decrease in both k_La_{20} and α-factor.
- k_La_{20} and α-factor were affected by the same parameters: the volumetric airflow rate, the MLSS concentration (and its correlated parameters: MLVSS and viscosity), the SMP_{COD} and the EPS_c.
- MLSS was the main parameter controlling k_La_{20} and α-factor. MLSS should be kept below 10-15 $g.L^{-1}$ to improve the oxygen transfer efficiency.
- The presence of SMP_{COD} had a negative effect on the oxygen transfer, which could be explained by the presence of surfactants.
- EPS_c, by facilitating the formation of large flocs, increased the porosity of the flocs and therefore their diffusivity, which was beneficial to the oxygen transfer.

Acknowledgements

The authors would like to acknowledge Thames Water for their financial support and Copa MBR for providing sludge samples. Felix Nelles was supported by an EC Erasmus grant.

The views expressed in this paper are those of the authors and do not necessarily represent those of their respective organisations.

References

APHA, AWWA, and WEF. (1998). "Standards methods for the examination of water and wastewater." American Public Health Association, American Water Works Association and Water Environment Federation, Washington DC, USA.

Badino, J., A. C., Facciotti, M. C. R., and Schmidell, W. (2001). Volumetric oxygen transfer coefficients (kLa) in batch cultivations involving non-Newtonian broths. Biochemical Engineering Journal **8,** 111-119.

Carvalho, G., Novais, J. M, Vanrolleghem, P. A., Pinheiro, H. M. (2002), Optimal operation for timely adaptation of activated sludge plants to changes in surfactant composition of wastewater, *Wat. Sci. Tech.* **45** (4-5), 345-353.

Chang, I. S., and Lee, C. H. (1998). Membrane filtration characteristics in membrane-coupled activated sludge system - the effect of physiological states of activated sludge on membrane fouling. Desalination **120,** 221-233.

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

Dubois, M., Gilles, K. A., Hamilton, J. K., Rebers, P. A., and Smith, F. (1956). Colorimetric method for determination of sugars and related substances. Analytical Chemistry **28,** 350-356.

Freitas, C., and Teixeira, J. A. (2001). Oxygen mass transfer in a high solids loading three-phase internal-loop airlift reactor. Chemical Engineering Journal **84**, 57-61.

Fujie, K., Hu, H.-Y., Ikeda, Y., and Urano, K. (1992). Gas-liquid oxygen transfer characteristics in an aerobic submerged biofilter for the wastewater treatment. Chemical Engineering Science **47**, 3745-3752.

Garcia-Ochoa, F., Castro, E. G., and Santos, V. E. (2000). Oxygen transfer and uptake rates during xanthan gum production. Enzyme and Microbial Technology **27**, 680-690.

Germain, E., Stephenson, T. and Pearce, P. (2005) Biomass characteristics and membrane aeration: Toward a better understanding of membrane fouling in submerged membrane bioreactors (MBRs). Biotechnology and Bioengineering **90**(3), 316-322.

Germain, E. and Stephenson, T. (2005) Biomass characteristics, aeration and oxygen transfer in membrane bioreactors: their interrelations explained by a review of aerobic biological processes. Re/views in Environmental Science and Bio/Technology, *in press*.

Günder, B. (2001). "The Membrane Coupled-Activated Sludge Process in Municipal Wastewater Treatment." Technomic Publishing Company Inc., Lancaster, USA.

Hair, J. F., Anderson, R. E., Tatham, R. L., and Black, W. C. (1998). "Multivariate data analysis." Prentice-Hall International Inc., Upper Saddle River, NJ, USA.

Hong, S., Bae, T., Tak, T., Hong, S., and Randall, A. (2002). Fouling control in activated sludge submerged hollow fiber membrane bioreactors. Desalination **143,** 219-228.

Houghton, J. I., Burgess, J. E. and Stephenson, T. (2002) Off-line particle size analysis of digested sludge. Water Research **36** (18), 4643-4647.

Jin, B., Yu, Q., Yan, X. Q., and van Leeuwen, J. H. (2001). Characterization and improvement of oxygen transfer in pilot plant external air-lift bioreactor for mycelial biomass production. World Journal of Microbiology & Biotechnology **17,** 265-272.

Ju, L.-K., and Sundararajan, A. (1994). The effects of cells on oxygen transfer in bioreactors: physical presence of cells as solid particles. The Chemical Engineering Journal and the Biochemical Engineering Journal **56,** B15-B21.

Koide, K., Shibata, K., Ito, H., Kim, S. Y., and Ohtaguchi, K. (1992). Gas holdup and volumetric liquid-phase mass transfer coefficient in a gel-particle suspended bubble column with draught tube. Journal of Chemical Engineering of Japan **25,** 11-16.

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

Kraume, M., Bracklow, U., Vocks, M., and Drews, A. (2005). Nutrients removal in MBRs for municipal wastewater treatment. Water Science & Technology **51,** 391-402.

Lee, W., Kang, S., and Shin, H. (2003). Sludge characteristics and their contribution to microfiltration in submerged membrane bioreactors. Journal of Membrane Science **216,** 217-227.

Mueller, J. A., Boyle, W. C., and Popel, H. J. (2002). "Aeration: principles and practice." CRC Press, Boca Raton, USA.

Muller, E. B., Stouthamer, A. H., Vanverseveld, H. W., and Eikelboom, D. H. (1995). Aerobic Domestic Waste-Water Treatment in a Pilot-Plant With Complete Sludge Retention by Cross-Flow Filtration. Water Research **29,** 1179-1189.

Ozbek, B., and Gayik, S. (2001). The studies on the oxygen mass transfer coefficient in a bioreactor. Process Biochemistry **36,** 729-741.

Rosenberger, S. (2003). Charakterisierung von belebtem Schlamm in Membranbelebungsreaktoren zur Abwasserreinigung, Dissertation, TU Berlin, Fortschr.-Ber. VDI Reihe 3 Nr. 769, VDI-Verlag, Düsseldorf.

Stephenson, T., Judd, S. J., Jefferson, B., and Brindle, K. (2000). "Membrane Bioreactors for Wastewater Treatment." IWA Publishing, London, UK.

van der Roest, H., Leenen, J., Hofstra, M., Boeve, J., and van der Vlist, J. (2001). The Dutch contribution to the MBR development in perspective. H20**,** 7-10.

Van Weert, G., Van Der Werff, D., and Derksen, J. J. (1995). Transfer of O_2 from air to mineral slurries in a rushton turbine agitated tank. Minerals Engineering **8,** 1109-1124.

Verlaan, P., and Tramper, J. (1987). Hydrodynamics, axial dispersion and gas-liquid oxygen transfer in an airlift-loop bioreactor with three-phase flow. In "International Conference on Bioreactors and Biotransfomations", pp. 363-373, Elsevier, London UK.

WEF, and ASCE. (2001). "Aeration-A wastewater treatment process." Water Environment Federation, New York, USA.

Wingender, J., Flemming, H.-C., Neu, T. R. (1999) Introduction - What are bacterial extracellular polymeric substances? In: Wingender, J., Neu, T. R., Flemming, H.-C. (eds) Microbial extracellular polymeric substances. Springer Verlag, Berlin, pp 1-19.

Zhang, X., Bishop, P. L., and Kinkle, B. K. (1999). Comparison of extraction methods in quantifying extracellular polymers in biofilms. Water Science & Technology **39,** 211-218.

Table 1. Biomass and plant characteristics of the submerged MBR sludges studied.

Plant	A	A	B	C	D	E	F	D	G	G
MLSS ($g.L^{-1}$)	7.2	9.3	12.0	13.7	13.9	16.8	17.3	17.9	28.9	30.2
MLVSS ($g.L^{-1}$)	5.3	6.9	8.7	10.8	10.4	13.4	13.9	13.2	19.5	19.3
EPS_c ($mg.L^{-1}$)	111.4	265.5	167.0	184.1	175.3	226.2	201.8	130.1	252.2	154.1
EPS_p ($mg.L^{-1}$)	711.0	919.7	873.0	874.0	734.5	924.5	1216.0	1222.0	865.0	828.0
EPS_{COD} ($mg.L^{-1}$)	1442	1873	1802	1788	1570	1736	1846	1814	1536	1798
SMP_c ($mg.L^{-1}$)	4.63	7.00	3.44	15.25	9.94	7.75	9.38	9.75	20.75	8.56
SMP_p ($mg.L^{-1}$)	4.50	10.00	27.50	25.50	9.50	41.50	61.00	63.00	57.00	22.0
SMP_{COD} ($mg.L^{-1}$)	72	54	72	180	108	198	180	136	106	90
Viscosity @ 12.24 s^{-1} (mPa.s)	13.3	39.8	10.8	75.8	44.6	55.9	99.3	87.6	122.3	213.0
MMD (μm)	88.9	68.0	85.4	62.1	60.9	42.5	80.4	70.2	38.5	43.1
Plant scale	PP	PP	FS	PP	FS	FS	FS	FS	FS	FS
Type of membrane	Zenon	Zenon	Kubota	Kubota	Kubota	Kubota	Kubota	Kubota	Kubota	Kubota
Membrane area (m^2)	122	122	7680	5.6	1600	2880	320	1600	60	60

PP: pilot plant scale; FS: full scale; $_c$: carbohydrate; $_p$: protein.

Table 2. Pearson-*r* correlation matrix of the characteristics of the biomass studied for their impact on oxygen transfer.

	MLVSS	SMP_{COD}	EPS_{COD}	SMP_p	EPS_p	SMP_c	EPS_c	MMD	Viscosity
MLSS	**0.98**	0.36	-0.11	0.78	0.31	0.80	0.41	-0.70	**0.86**
	MLVSS	0.51	-0.02	0.83	0.40	0.78	0.41	-0.70	**0.89**
		SMP_{COD}	0.28	0.55	0.46	0.32	0.06	-0.38	0.53
			EPS_{COD}	0.31	0.69	-0.19	0.28	0.13	0.11
				SMP_p	0.80	0.44	0.14	-0.30	0.80
					EPS_p	0.05	0.03	0.09	0.55
						SMP_c	0.41	-0.70	0.84
							EPS_c	-0.63	0.37
								MMD	-0.55

Table 3. *Beta coefficients* and statistical significance parameters obtained by regression analysis for k_La_{20}.

MLSS	-0.66
aeration	0.56
EPS_c	0.33
COD_{SMP}	-0.31
R^2	80%
F	$F_{(4,39)}=38.9$
p-level	<0.001

Table 4. *Beta coefficients* and statistical significance parameters obtained by regression analysis for α-factor.

MLSS	-0.75
COD_{SMP}	-0.40
EPS_c	0.38
aeration	0.21
R^2	89%
F	$F_{(4,39)}=91.2$
p-level	<0.001

Biomass effects on oxygen transfer in membrane bioreactors.

Germain, Eve

2007-03

Germain E, Nelles F, Drews A, et al., (2007) Biomass effects on oxygen transfer in membrane bioreactors, Water Research, Volume 41, Issue 5, March 2007, pp. 1038-1044

http://dx.doi.org/10.1016/j.watres.2006.10.020