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Biomass characteristics, aeration and oxygen transfer in membrane bioreactors: Their interrelations explained by a review of aerobic biological processes

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Abbreviations: a – gas–liquid interfacial area based on aerated liquid volume (L^{-1}); K – mass transfer coefficient ($L\ t^{-1}$); k_L – gas–liquid mass transfer coefficient ($L\ t^{-1}$); k_La – overall volumetric gas–liquid mass transfer coefficient (t^{-1}); α – ratio of k_La in process water to clean water; $\alpha\ k_L$a – characteristic of the aeration capacity (t^{-1}); η – viscosity ($L^{-1}\ M\ t^{-1}$); Unit dimensions: L – length; M – mass; t – time

Abstract

Membrane bioreactor (MBR) is a promising alternative to conventional wastewater treatment methods. However this process is still under-used due to its high running costs. Its main power requirement comes from aeration, which is used to supply dissolved oxygen to the micro-organisms and to maintain the solids in suspension. In addition, in submerged MBRs, aeration is used for membrane cleaning. A complex matrix links the biomass characteristics, the aeration and the oxygen transfer. These parameters can impact on each other and/or delete one another effect. In order to understand the phenomena occurring in MBRs, similar aerobic biological processes, such as fermentation, mineral industry and slurry, were investigated. This review discusses the interrelations of the biomass characteristics (solids concentration, particle size and viscosity), the aeration intensity and the oxygen transfer in MBRs.

1. Introduction

Combining membrane technology with biological treatment, the membrane bioreactor (MBR) is an alternative to conventional wastewater treatment methods (Stephenson et al. 2000). Wastewater, as in the activated sludge process, is treated by biomass in an aerated mixed tank before being filtered. The sedimentation stage of the conventional activated sludge process is replaced by a membrane filtration stage. An almost solids-free permeate passes through the membranes, whereas micro-organisms are retained in the tank. Thus the mixed liquor can be concentrated, resulting in a small bioreactor footprint and an excellent quality treated water. However, operating with membranes at high solids concentration presents some disadvantages. The major process problem with MBRs remains membrane fouling due to the interaction between the membrane material and the components in the activated sludge liquor (Chang & Fane 2001). The MBR main power requirement comes from aeration, which is used for supply of dissolved oxygen (DO) for metabolism and to maintain solids in suspension. The biological aeration requirements are higher than in conventional activated sludge process due to the higher oxygen demand initiated by highly concentrated biomass. Additionally, aeration is used for membrane cleaning purposes in submerged MBRs, where membrane cleaning is provided by air scouring and by fibres agitation in the case of hollow fibres membranes.

As biomass and aeration characteristics have an effect on each other, two topics should be considered when studying aeration operations in MBRs:

- the effects of biomass components on aeration efficiency, represented by the oxygen transfer parameters,
- the effects of aeration (intensity and type of diffusers) on biomass characteristics.

As in all aerobic biological systems, biomass contained in the MBR requires oxygen to perform diverse chemical reactions. The right amount of oxygen needs to be provided to the micro-organisms and wastewater, in response to their three specific demands:

- carbonaceous biochemical oxygen demand (BOD): conversion of the carbonaceous organic matter in wastewater to cell tissue and various gaseous end products,
- nitrogenous BOD: ammoniacal nitrogen is oxidised to the intermediate product nitrite, which is then converted to nitrate; this process is nitrification,
- inorganic chemical oxygen demand (COD): oxidation of reduced inorganic compounds within the wastewater.

The amount of oxygen diffusing in the mixed liquor is characterised by the oxygen mass transfer coefficient. This mass transfer coefficient is one of the general parameters used to describe the diffusion of particles from regions of high concentration into regions of lower concentration. This approach assumes that the diffusion occurs across an interface. The basic model for mass transfer is:

$$\begin{aligned}&(\text{rate of mass transferred})\\&\quad = k(\text{interfacial area})(\text{concentration difference}),\end{aligned} \tag{1}$$

where k is the mass transfer coefficient (Cussler 1997).

The main parameter used to characterise the oxygen transfer in aeration processes is the overall mass transfer coefficient, $k_{\mathrm{L}}a$; where k_{L} represents the mass transfer coefficient based on the liquid film resistance and a, the interfacial area. Another parameter commonly used to describe the oxygen transfer in biological aerated systems is the *α-factor*. This correction factor is defined as the ratio between $k_{\mathrm{L}}a$ in the process solution and $k_{\mathrm{L}}a$ in clean water. It accounts for the effect of process water characteristics on the oxygen transfer coefficient.

In MBRs, like in all aerobic wastewater processes, both by the biomass characteristics and the design of the aeration system are affecting the oxygen transfer (Mueller et al. 2002). Biomass is a heterogeneous mixture of particles, micro-organisms, colloids, organic polymers and cations, which all have different shapes, sizes and densities. All these parameters have an impact on oxygen transfer. 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. 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).

On the other hand, MBR properties are affected by aeration. Changes in airflow rate affect the biological and physical characteristics of the mixed liquor. Species diversities differ depending of the amount of oxygen available in the solution (Madoni et al. 1993). Mixing intensity, resulting from aeration, affects the shape and size of particles by breaking-up sludge flocs (Abbassi et al. 1999).

Many correlations linking oxygen transfer and aerobic biological system characteristics are found in the literature, simple or complex, depending on the parameters considered (Fujie et al. 1992; Van Weert et al. 1995; Boumansour & Vasel 1998; Abbassi et al. 1999; Chang et al. 1999; Chang & Fane 2000; García-Ochoa et al. 2000; Hebrard et al. 2000; Badino et al. 2001, 2001; Chern et al. 2001; Lu et al. 2001; Ozbek & Gayik 2001; Ozaki & Yamamoto 2001; Chisti & Jauregui-Haza 2002; Garrido Hoyos et al. 2002). However, these correlations are difficult to apply to other systems than the one they are characterising.

This review looks at the MBR parameters independently and collectively, providing a better understanding of the oxygen transfer occurring in MBRs and the effects of aeration on MBR biomass. The review was extended to similar aerobic biological systems such as fermentation, mineral industry and slurry, to provide insights into MBR operation.

2. Particle concentration

The impact of solids concentration on the oxygen transfer has been studied by many authors for a wide range of systems and different kinds of particles (Table 1). Despite the differences between the systems and the solids characteristics used, high solids concentrations affected the oxygen transfer in the same way, i.e. reducing oxygen transfer. Nevertheless, the drop observed in the oxygen transfer while increasing the solids concentration is more or less important depending on the characteristics of the system.

The decrease or increase of the oxygen transfer coefficient is not linear with changes in the solids concentration. The results obtained in an agitated bioreactor for the mineral industry demonstrated that, while increasing the concentration of sand particles from 0 to 40 vol.% solids, the decline in oxygen transfer efficiency was not of the same importance for the different concentration ranges. Between 0 and 10 vol.% solids and between 30 and 40 vol.% solids, the decrease of oxygen transfer was more significant than between 10 and 30 vol.% solids (Van Weert et al. 1995). Data from a fermentation bioreactor with a cell concentration range of 0–5 g l^{-1} showed the same trend. The total decrease of k_La reached 30% over the concentration range, with a 15% decrease between 0 and 1 g l^{-1} (Ju & Sundararajan 1994). The accumulated cells near the interface may have formed a layer that diminished the oxygen transfer. This phenomenon was defined as the physical blocking effect (Bungay & Masak 1981; Ju & Sundararajan 1994).

Freitas & Teixeira (2001), Verlaan & Tramper (1987) and Ozbek & Gayik (2001) established that an increase in particle concentration did not affect the two parameters of the overall mass transfer coefficient, k_L and a, with the same significance. The augmentation of the solids concentration increased the coalescence process, which reduced the interfacial area a. Nevertheless, the solids loading seemed to have only a minor effect on the mass transfer coefficient k_L. In an internal-loop airlift reactor, the k_La diminution corresponding to the increase of solids concentration was stronger for riser gas velocities higher than 0.075 m s^{-1}. Up to this value the effect of solids loading on the mass transfer coefficient was negligible. The amount of gas in the system was so low that the coalescence process was not affected significantly by the presence of the solids (Freitas & Teixeira 2001).

A small increase in the solids loading can, however, initially lead to a better mass transfer coefficient. In an airlift bioreactor for fermentation, the increase of mycelial pellets concentration had a positive effect on k_La up to a certain level (6.68 g l^{-1}), then the oxygen transfer efficiency decreased with further addition of solids (Klein et al. 2002). Smith & Skidmore (1990) and Saba et al. (1987) noticed a stabilisation of k_La before the decrease. Diverse explanations for this phenomenon have been given in the literature. Smith & Skidmore (1990), working with very small particles, explained it by both the disrupting and the blocking effects of fine particles on the liquid surrounding air bubbles. Klein et al. (2002), working with bigger particles (Table 1), based their interpretation of the k_La decline on the interaction of pellets with bubbles, promoting more intensive bubble coalescence and break-up events in the bioreactor. Both the size and the frequency of coalesced bubbles slightly increased with increasing biomass. The rate of mass transfer is proportional to the contact area between the liquid and the oxygen phases, therefore small bubbles have a higher contact area/volume ratio compare to coarse bubbles at equal airflow rates, making them more efficient in terms of k_La.

Mixed liquor suspended solids (MLSS) concentrations for MBRs are typically between 10 and 20 g l^{-1}. The range starts from 2 to 80 g l^{-1} (Stephenson et al. 2000). The biomass concentration range is so wide that all the phenomena described can be expected to happen in MBRs. However, several studies observed an exponential relationship between α-*factor* and MLSS concentration. Muller et al. (1995), found α-*factor* values of 0.98, 0.5, 0.3 and 0.2 for MLSS concentrations of 3, 16, 26 and 39 g l^{-1} respectively. An

Table 1. Systems studied for particles concentration and size

Application area	Solids type	Solids concentration	Particle size	System	Oxygen transfer parameter	Reference
Aerobic biological system	Scotch-Brite pieces (green pad)	0–25% v/v	0.65× 0.5 × 0.5 cm 0.65× 1× 1 cm 0.65× 1.5× 1.5 cm	Bioreactor	k_La	Ozbek & Gayik (2001)
Cultivation of mycelial micro-organisms	Biomass	2–8 g l^{-1}	nd	Airlift bioreactor	k_La	Jin et al. (2001)
Fermentation	Mycelial pellets (*Aspergillus niger*)	4–12 g dm^{-3}	0.7 mm	Airlift bioreactor	k_La	Klein et al. (2002)
Fermentation	Heat-sterilised cells	nd	nd	Sparged stirred fermentor, tower fermentor	k_La	Yagi & Yoshida (1974)
Fermentation	Cells (non-respiring live baker's yeast)	0–5 g l^{-1}	nd	Bioreactor	k_La	Ju & Sundararajan (1994)
Fermentation	Ca-alginate beads	0–30% v/v	2 mm	Airlift bioreactor	k_La	Freitas & Teixeira (2001)
Fermentation	Polystyrene cylinders	0–30% v/v	2.4 mm	Airlift bioreactor	k_La	Hwang & Lu (1997)
Fermentation	Biomass (Xanthan gum production)	0–1.5 kg m^{-3}	nd	Stirred tank	k_La	García-Ochoa et al. (2000)
Fermentation	Cellulose fibre solids	0–4% w/v (g/100 ml)	290 μm	Airlift bioreactor	k_La	Chisti & Jauregui-Haza (2002)
Mineral industry	Glass beads	0–40% v/v	66 μm	Agitated bioreactor	k_La	Mills et al. (1987)
Mineral industry	Sea sand, Al_2O_3, Fe_2O_3, Kieselgurh, TiO_2, ZnO	0–0.1% v/v	nd	Stirred tank	k_La	Oguz et al. (1987)
Mineral industry	Sand particles	0–40% v/v	14 μm	Agitated bioreactor	k_La	Van Weert et al. (1995)
Slurry	Gel particles	0–20% v/v	1.88–3.98 mm	Bubble column	nd	Koide et al. (1992)
Wastewater treatment	Biomass	nd	nd	Activated sludge tank	$\alpha\ k_La$	Chatellier & Audic (2001)
Wastewater treatment	Biomass	3–39 g MLSS l^{-1}	nd	Cross-flow membrane bioreactor	α-*factor*	Muller et al. (1995)
Wastewater treatment	Biomass	0–30 g MLSS l^{-1}	nd	Activated sludge reactor	α-*factor*	Krampe & Krauth (2003)
Wastewater treatment	Biomass	0–30 g MLSS l^{-1}	nd	Membrane bioreactor	α-*factor*	Günder (2001)
Wastewater treatment	Biomass	3.5 g MLSS l^{-1}	130 μm	Membrane bioreactor	nd	Chang et al. (1999)
Wastewater treatment	Polymer granulate	0–100 g l^{-1}	2.7 mm	Airlift bioreactor	k_La	Lindert et al. (1992)
Wastewater treatment	Polystyrene rod	nd	3× 3(long) mm	Biofilter	k_La	Fujie et al. (1992)
Wastewater treatment	Polyvinylalchol gel (irregular)	nd	8 mm	Biofilter	k_La	Fujie et al. (1992)
Wastewater treatment	Anthracite (splinter)	nd	2, 3, 5 mm	Biofilter	k_La	Fujie et al. (1992)
Wastewater treatment	Ceramic ball (sphere)	nd	6, 9, 13, 23 mm	Biofilter	k_La	Fujie et al. (1992)

exponential equation representing the impact of the solids concentrations on the α-*factor* could be calculated from this data, with an R^2 of 0.99 (Figure 1). Günder (2001) and Krampe & Krauth (2003) observed the same trend but with lower α-*factor* values (Figure 1). Oxygen transfer in MBRs decreased exponentially with increasing solids concentration. However, the solids concentration can easily be controlled by applying constant solids retention time (SRT) and hydraulic retention time (HRT) to attain a targeted solids concentration or by irregularly wasting sludge with the aim to keep the solids concentration around a targeted value (Stephenson et al. 2000). By operating at lower solids concentrations (below 15 g l^{-1}), the oxygen transfer could be significantly improved (Figure 1).

3. Particle size

Aeration, mass transfer and particle size all interact with each other. Airflow variations have a dual effect on biological systems: on oxygen concentration available in the solution and on mixing intensity. Both of these effects influence the size of the particles. No clear relationship characterising the DO concentration effect on activated sludge flocs size has been found. However, larger flocs have been observed at higher DO concentrations (Wilen & Balmer 1999).

An increase in airflow, to produce a higher oxygen concentration, results in a greater mixing intensity. The shear stress applied on the activated sludge flocs is affected, inducing floc break-up, and so particles of different sizes are formed. Therefore the difference noticed in floc size when increasing the airflow does not only come from the amount of oxygen in the solution, but also from the rise in mixing intensity (Abbassi et al. 1999). Laboratory scale experiments, looking at the reduction of excess sludge production in wastewater treatment technology, have been undertaken to characterise the effects due to the oxygen concentration, independently of the mixing intensity, on activated sludge flocs. At a sludge loading of 0.53 kg BOD_5 kg $MLSS^{-1}$ d^{-1}, the excess sludge production was reduced by 22% by raising the oxygen concentration from 2 to 6 mg l^{-1} (Abbassi et al. 1999). 10% of the break-up events were a result of the mixing intensity, while 12% were a result of an increase in the mixed liquor oxygen concentration. Higher mixing intensity and DO concentration, created by raising the airflow, had almost the same impact on the floc break-up, and therefore on the particle size.

The modification observed in the mass transfer coefficient while increasing the solids loading is dependent on the particle size. With fine particles, up to 0.01 mm, k_La increased with increasing solids concentration up to a certain level and remained stable before decreasing with further solids loading (Saba et al. 1987; Smith & Skidmore 1990). With large particles, around 1–3 mm, an increase in the solids concentration led

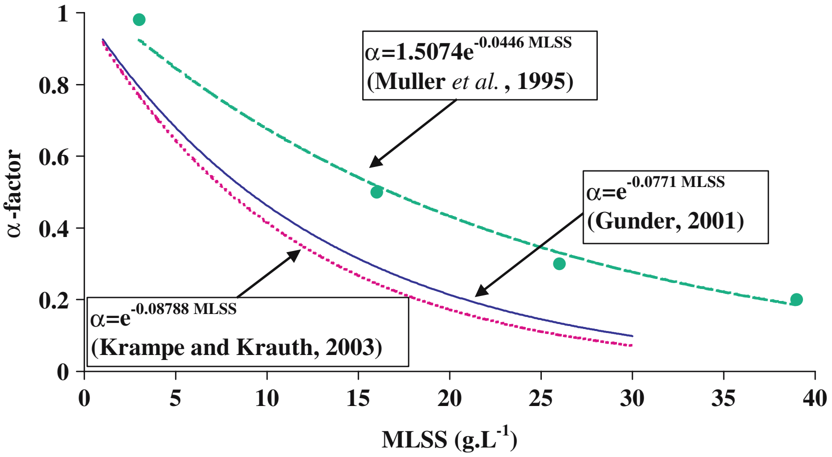

Figure 1. Alpha factor vs. MLSS concentrations.

directly to a decrease in the k_La (Koide et al. 1992; Lindert et al. 1992; Komaromy & Sisak 1994; Hwang & Lu 1997; Nakao et al. 1999). The behaviour of the mass transfer coefficient may also change when very large particles are used. In systems containing packing materials or biomass support, the oxygen coefficient increased with larger particles (Fujie et al. 1992; Ozbek & Gayik 2001). The smallest materials brought about bubble coalescence, while smaller bubbles were obtained with very large packing materials. Turbulence produced might be more violent with bigger particles. Nevertheless, Koide et al. (1992) noticed no modification in k_La while increasing the diameter from 1.88 to 3.98 mm of gel particles in a bubble column.

Particle size differs, from one MBR to another, because of the type of MBR and the characteristics of aeration, biomass and wastewater (Table 2). In a sidestream system, activated sludge is recirculated by means of a pump (Stephenson et al. 2000). In the membrane unit, cross-flow rate is kept high, to avoid a cake layer to build-up on the membrane surface. High pressure allows a constant permeate flux to be maintained through the membrane. These processes apply a high shear stress on the flocs and break them up, reducing the particle size. In a submerged MBR, the cross-flow velocity is obtained by aeration and the suction pressure is lower. The forces applied on flocs are weaker, allowing bigger particles to be contained in the bioreactor. Wisniewski & Grasmick (1998) studied the effects of the recirculation on the particle size in a sidestream MBR. Without recirculation, flocs size ranged from 20 μm to more than 500 μm. Only 15% of the particles were lower than 100 μm. With recirculation, reduction in particle size was directly proportional to the magnitude of the shear stress and the experiment time. At linear velocities in the membrane module of 0.5 and 5 m s^{-1}, 55 and 98% of the particles were lower than 100 μm respectively. Activated sludge flocs were destroyed by the recirculating pump. In a sidestream MBR operated at a SRT > 3500 d, the mixed liquor consisted of a dense suspension of free cells, very small flocs (< 50 μm) and floc fragments (Muller et al. 1995). Lee et al. (2003), observed floc sizes ranging from 1 to 280 μm in a submerged MBR with volatile suspended solids (VSS) concentrations comprised between 2.8 and 5.5 g l^1. The mean particle size varies significantly from one MBR to another but also inside an MBR where large particle size distributions are found and particle sizes can range from a few μm to 500 μm.

4. Viscosity effect

An increase in viscosity has been shown to have a negative influence on the oxygen transfer coefficient (Koide et al. 1992; García-Ochoa et al. 2000; Badino et al. 2001; Jin et al. 2001; Ozbek & Gayik 2001), the systems and the viscosity ranges studied are shown in Table 3. Different

Table 2. Mean particle sizes in MBRs

Type	Solids concentration	Velocity in the membrane module	Mean particle size	Reference
S	0.2–0.5 g MLSS l^{-1}	na	30–40 μm	Zhang et al. (1997)
S	0.4–0.8 g MLSS l^{-1}	na	20–30 μm	Zhang et al. (1997)
S	3.5 g MLSS l^{-1}	na	130 μm	Chang et al. (1999)
S	0.5–1.0 g SS l^{-1}	na	14.82 μm	Huang et al. (2001)
S	7 g SS l^{-1}	na	30.61 μm	Huang et al. (2001)
S	2.8 g VSS l^{-1}	na	5.2 μm	Lee et al. (2003)
S	4.4 g VSS l^{-1}	na	6.0 μm	Lee et al. (2003)
S	6.6 g VSS l^{-1}	na	6.6 μm	Lee et al. (2003)
SS	0.2–0.5 g MLSS l^{-1}	nd	7–8 μm	Zhang et al. (1997)
SS	10–15 g SS l^{-1}	5 m s^{-1}	20 μm	Wisniewski & Grasmick (1998)
SS	10–15 g SS l^{-1}	0.5 m s^{-1}	125 μm	Wisniewski & Grasmick (1998)
SS	11–13 g TSS l^{-1}	20 l min^{-1}	3.5 μm	Cicek et al. (1999)

S: submerged, SS: side stream..

explanations concerning this phenomenon have been given in the literature. Bubble coalescence is influenced by viscosity, resulting in modifications in bubble size distribution. Experiments conducted with addition of glycerol to increase the viscosity demonstrated that at high viscosity, large bubbles were formed (Ozbek & Gayik 2001). Air became less well distributed throughout the process fluid and k_La decreased. In the case of mycelial biomass production, large spherical-capped bubbles rose rapidly, while smaller bubbles remained trapped inside the reactor (Jin et al. 2001). Oxygen solubility was lowered by the highly viscous solution. Resistance to oxygen transfer, from the gaseous to the liquid phase, was increased (Badino et al. 2001).

Typical viscosity values for MBRs are presented in Table 4. Krampe & Krauth (2003) and Günder (2001) formulated equations linking the *α-factor* to the representative viscosity at a shear rate of 40 s^{-1} in high MLSS concentration activated sludge (Table 5). The negative relationship was clearer at high viscosity (Krampe & Krauth 2003). The *α-factor* was better correlated to the viscosity than to the MLSS concentration (Wagner et al. 2002). Activated sludge has been characterised as a non-Newtonian pseudoplastic fluid. Increasing the shear stress led to a decrease in viscosity (Dick & Ewing 1967; Stephenson et al. 2000; Wagner et al. 2002). An increase in aeration rate has a double beneficial effect on the oxygen transfer: it increases the amount of oxygen available in the MBR and decreases the biomass viscosity by increasing the shear stress. Viscosity is also correlated to the solids concentration: viscosity increased exponentially with increasing MLSS concentration (Sato & Ishii 1991; Manem & Sanderson 1996), negatively affecting the oxygen transfer.

5. Discussion

Aeration plays an important role in MBR operations and represents its major power input (Stephenson et al. 2000). To allow MBRs to be competitive to conventional wastewater treatment plants, these additional costs need to be reduced. Particle concentration, particle size and viscosity are the main parameters characterising the biomass and known to have an effect on the

Table 3. Systems studied for viscosity effects on oxygen mass transfer

Application area	System	Particles	Fluid behaviour	Viscosity (Pa s)	k_La (min^{-1})	Reference
Fermentation	External airlift bioreactor	Mycelial culture broths (*Rhizopus oligosporus*)	non-Newtonian pseudoplastic	6340	nd	Jin et al. (2001)
				12,400		
				18,600		
Fermentation	Bioreactor	Fermented broth (*Aspergillus awamori*)	non-Newtonian pseudoplastic	0.013–0.257	6.35–2.07	Badino et al. (2001)
Fermentation	Bioreactor	Biomass (*Xanthomonas campestris*)	non-Newtonian pseudoplastic	0.001–0.168	nd	García-Ochoa et al. (2000)
Aerobic biological system	Bioreactor	Glycerol	nd	0.001–0.566	2.65–0.083	Ozbek & Gayik (2001)
Wastewater treatment	Aerated container	Activated sludge	non-Newtonian pseudoplastic	0.005–0.105	nd	Krampe & Krauth (2003)
Slurry	Bubble column	Gel particles	nd	0.001–0.013	nd	Koide et al. (1992)
Mineral industry	Agitated tank	Sand	nd	0.001–0.062	nd	Van Weert et al. (1995)
Fermentation	Airlift bioreactor	Fermentation broths (*Aspergillus niger*)	Newtonian	0.001	nd	Klein et al. (2002)

Table 4. Viscosity in MBRs

System	MLSS concentration (g l^{-1})	Viscosity (mPa s)	Reference
Sidestream MBR	13–57	8.5–75	Rosenberger et al. (2000)
Submerged MBR	6–25	20–80	Nagaoka et al. (1996)
Sidestream MBR	20–26	406–745 at 30 rpm	Sato & Ishii (1991)

oxygen transfer. These three biomass parameters and aeration are interrelated (Figure 2). The aeration intensity affects the particle size and the viscosity, while solids concentration modifies the viscosity. Their individual effect on oxygen transfer can be modified by the added effect of another parameter, especially for particle size and concentration.

In most cases, the changes in k_La are related to modifications of the air bubbles. Fine bubbles aerators are commonly used in MBRs, yet coarse bubble aeration is seen in submerged MBRs to reduce membrane fouling (Cornel et al. 2003). Fine bubble aeration remains the most efficient system, small bubbles having a higher contact area/volume ratio increasing the term a of the oxygen transfer coefficient k_La. However, in MBRs the bubble size is often altered by coalescence and break-up events initiated by the biomass characteristics. Bubble coalescence may occur when operating at high solids concentration, in presence of small particles or at high viscosity. Therefore fine bubble aeration becomes less efficient and the k_La values move towards coarse bubble aeration values. In contrast, smaller bubbles can be formed in presence of large particles, improving the oxygen transfer. However, in highly viscous biomass, small bubbles can stay trapped inside the MBR, leading to a poor distribution of the air (Jin et al. 2001).

Even if the mean particle size varies depending on the system design (in particular due to aeration and recirculation) and biomass characteristics, the actual range of particle size remains very wide from a few μm to more than 500 μm, especially for submerged MBRs. To improve the oxygen transfer efficiency, large particles will need to be formed. However, aeration in MBRs needs to sustain the oxygen demand from a high concentrated biomass, implying high aeration rate and so, high mixing intensity. Low mixing intensity, allowing large flocs to form, is difficultly to achieve in MBRs.

Table 5. Relationship between the α-*factor* and the representative viscosity at a shear rate of 40 l s^{-1}, in high MLSS concentration activated sludge

Relation	Reference
$\alpha = \eta_{r,40}^{-0.456}$	Günder (2001)
$\alpha = \eta_{r,40}^{-0.45}$	Krampe & Krauth (2003)

Bubble coalescence increased while operating at high solids concentration or high viscosity, reducing the oxygen transfer. These two parameters should be kept reasonably low. Particle concentration is the easiest parameter to control in MBRs. By operating at fixed SRT and HRTs, the solids concentration can be stabilised (Stephenson et al. 2000). Viscosity in MBRs is strongly correlated to the solids concentration; higher solids concentration leads to an exponential increase in viscosities (Sato & Ishii 1991; Manem & Sanderson 1996). Controlling the MBR solids concentration is a straightforward way of regulating the viscosity. However, high aeration rates, in addition to increasing the amount of oxygen, intensify the shear stress inside the MBR, leading to lower values for viscosity.

The biomass parameters affect the overall volumetric gas–liquid mass transfer coefficient, k_La, in different ways. The solids concentration affects the interfacial area, a, more than the gas–liquid mass transfer coefficient k_L. In contrast, the viscosity affects k_L more, the resistance applied to the oxygen transfer from the gas to the liquid phase being increased. The effects of particle size and solids concentration on oxygen transfer are interrelated. When increasing the solids concentration with fine particles (up to 0.01 mm), k_La increased up to a certain level and remained stable before decreasing with further solids loading. With large particles (around 1–3 mm), it led directly to a decrease in k_La. The second phenomenon is more likely to happen in MBRs, where the mean particle size is generally above

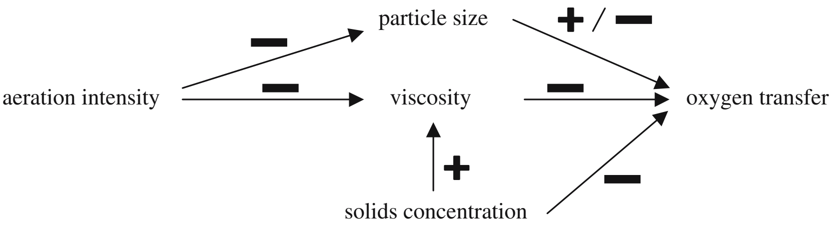

Figure 2. Summary of MBR biomass characteristics effects on oxygen transfer.

0.01 mm, and some particles easily reach 0.5 mm diameter.

The effects of aeration on the biomass are due to the amount of oxygen dispensed to the biomass and to the shear stress induced by the mixing intensity. The amount of oxygen available in the solution and the shear stress applied to the flocs are linked together by one parameter: the aeration intensity. These two phenomena have almost the same impact on the particle size, when increased, break-up events happen, forming smaller particles. The shear stress also affects the biomass viscosity. High shear stress leads to low viscosity values.

The oxygen transfer in MBRs can be improved by applying operating conditions affecting the biomass characteristics found to have an effect on the oxygen transfer. By controlling the amount of sludge wasted, the particle concentration can be adjusted around a targeted value (Stephenson et al. 2000). Viscosity being exponentially correlated to the particle concentration, a change in particle concentration will affect the viscosity. By keeping the particle concentration low, the viscosity would be kept low too, leading to a better oxygen transfer. However, the effect of the particle size on oxygen transfer could not be controlled. All the MBRs studied had large particle size distributions, suggesting that narrower particle size distributions would not be observed when changing the operating conditions.

Aeration, particle concentration, particle size and viscosity compensate each other effects on oxygen transfer. For a better understanding of the phenomena happening 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, studies on MBRs have limited the parameters considered to solids concentration and viscosity. Other biomass characteristics need to be investigated, such as soluble microbial products (SMP) and extracellular polymer substances (EPS). These compounds are produced by the microorganisms. SMP and EPS are both mainly of microbial origin (Wingeder et al. 1999). SMP is soluble and is part of the liquid phase, whereas EPS is bounded to the cells and therefore is part of the solid phase. 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). Therefore both compounds are likely to affect the oxygen transfer.

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