STATE OF THE ART ON MBR IN EUROPE

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ABSTRACT

In Membrane Bioreactors (MBRs) for wastewater treatment the secondary clarifier is replaced by a membrane filtration. This offers the advantages of a complete removal of solids as well as pathogenic germs at smaller footprint plants.

Meanwhile more than 30 plants in municipalities and more than 120 plants in industry are operated or under construction in Europe, most of them in Great Britain, Germany and Italy.

A severe disadvantage is the higher energy demand of MBRs which exceeds conventional activated sludge systems by a factor 2-3. This high energy consumption is mainly due to the coarse bubble aeration system installed directly underneath the membrane modules and operated to keep fouling under control. Investigations of the Oxygen Transfer Rate (OTR) and Standard Aeration Efficiency (SAE) in two existing full scale MBRs at different MLSS with both aeration systems respectively are reported. The SAE of the "crossflow" coarse bubble aeration system for fouling control is about three times lower than the fine bubble aeration system which provides oxygen supply. Thus for limitation of energy consumption the "crossflow" aeration should be optimised and be used only for fouling control.

KEYWORDS

Membrane bioreactors, realized MBRs in Europe, energy demand, oxygen transfer, sludge viscosity

INTRODUCTION

In industrial and municipal wastewater treatment membrane bioreactors (MBR) offer an alternative to conventional Activated Sludge Processes (ASP). Basically the membrane replaces the secondary clarifier. This overcomes the limitations to MLSS-concentrations of 3 to 5 kg MLSS/m³ of the conventional activated sludge process. Because the MLSS concentration is independent from sedimentation it can be increased significantly. MLSS values of up to 30 kg/m³ are reported. Most membrane bioreactors with submerged membranes are operated in the range of 10 to 15 kg/m³ MLSS. This means smaller foot print of the plants.

In addition, the effluent of the micro- or ultra filtration membranes with pore sizes of about 0.1 to 0.4 µm is free of suspended solids and basically free of pathogenic germs (viruses, bacteria, parasites), thus of higher quality compared to conventional effluent. As a matter of fact, the membrane not only replaces the secondary clarifier, but replaces treatment steps like sand filtration and UV-disinfection as well.

As a result, MBRs are of interest wherever high quality effluent is required, because of a sensitive receiving water body or quite often in combination with water reuse for irrigation or as process water in industry. Anyhow, one disadvantage of MBRs is the often reported higher specific energy demand.

First a probably incomplete overview of MBRs in Europe with priority to Germany follows before some results concerning the energy demand are presented.

STATE OF THE ART

Beginning in the mid of the Nineties in Great Britain, meanwhile more than 30 municipal WWTPs and at least 120 "industrial" treatment plants in Europe are equipped with membrane bioreactors.

Municipal MBRs in Europe

Table 1 summarizes the municipal MBRs in succession of countries. As the list might be incompletely, it gives a fair overview.

Table 1: Municipal MBRs (3/03)

Country	MBR	Membrane	Flux m^3/d *(P.E.)*	in operation since
United Kingdom	Greyabbey	Kubota	1,166	in 2003
	Skipsea	Kubota	1,300	in 2003
	Dittisham	Kubota	227	in 2003
	Lynmouth	Kubota	1,642	in 2003
	Kirubbin	Kubota	1,728	in 2003
	Longbridge	Kubota	1,555	in 2003
	Gardenstown	Kubota	692	2003
	Finstown	Kubota	278	2003
	Llangranog	Kubota	281	2003
	Lowestoft	Zenon	4,300	2002
	Moneyreagh	Kubota	580	2002
	Minehead	Kubota	260	2002
	Westbury	Kubota	4,700	2002
	Campbeltown	Zenon	6,500	2001
	Daldowie	Kubota	10,800	2001
	South Wraxall	Kubota	256	2001
	Swanage	Kubota	13,000	2000
	Porlock	Kubota	1,900	1998
	Kingston Seymour	Kubota	125	1995
Germany	Rödingen	Zenon	*(3,000)*	1999
	Markranstädt	Zenon	*(12,000)*	2000
	Knautnauendorf	Huber VRM	*(900)*	2002
	Schwägalp	Huber VRM	*(780)*	2003
	Monheim	Zenon	*(10,000)*	04/2003
	Waldmössingen	Zenon	*(2,600)*	in 2003
	Markkleeberg	Zenon	*(30,000)*	in 2003
	Nordkanal	Zenon	*(80,000)*	in 2003
France	Ile de Yeu	Zenon	2,260	
	Perthes en Gatinais	Zenon	900	
	Thelus	Zenon	183	
Spain	SPS S.A.	Zenon	400	
	Cepicma	Zenon	24	
	Cepicma Sun Granot	Zenon	23	
Italy	ASM Brescia	Zenon	38,000	2002
Netherland	Maasbommel, NL		480	

Belgium	Aquafin	Zenon	36	
Switzerland	Säntis	Zenon	40	

As can be seen the marked is dominated by two suppliers. Figure 1 shows the well known Kubota and Zenon systems. Two small plant in Germany are equipped with a quite new system called “Vacuum Rotation Membrane” (VRM), where 6 to 8 modules build up an element on a rotating disc (Figure 2).

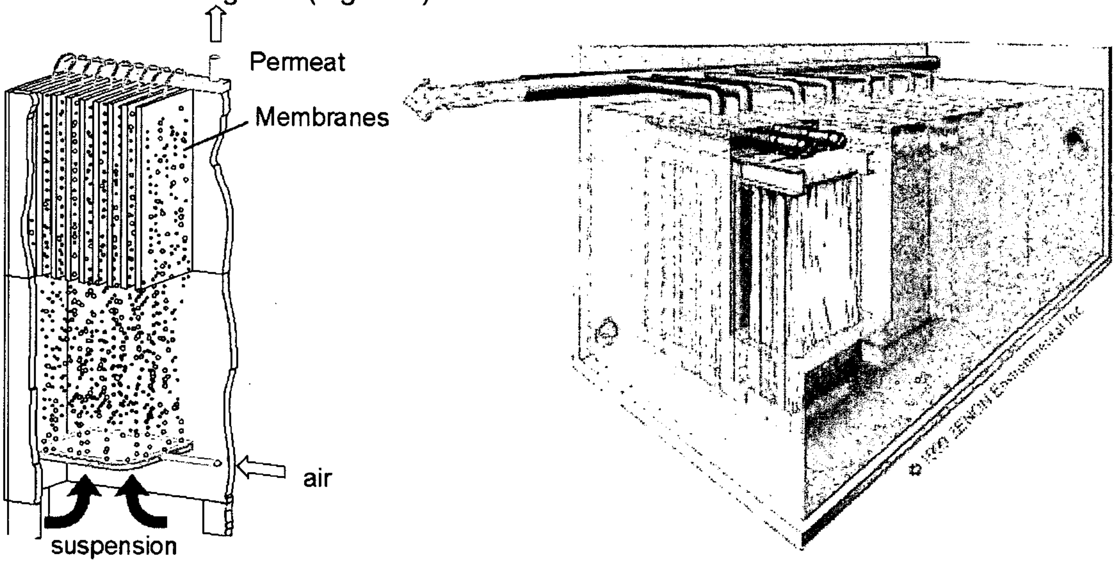

Figure 1: Kubota (l) and Zenon (r) membrane systems

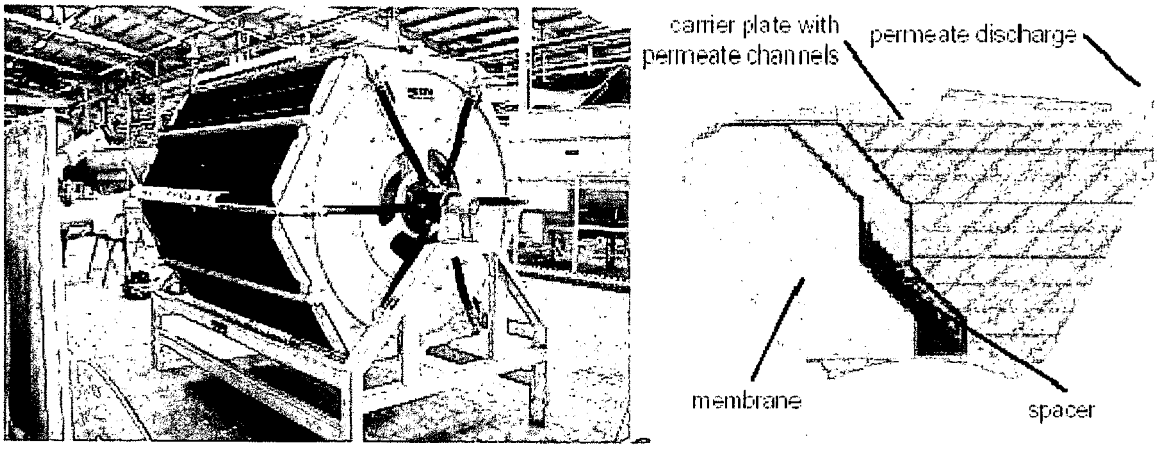

Figure 2: Huber Vacuum Rotating Membrane system (VRM system)

Industrial MBRs in Europe

A general survey of industrial plants is even more uncertain. A questionnaire dated in February 2002 resulted in the plants listed in table 2. Only plants with a throughput above 10 m³/d are listed.

Table 2: Industrial MBRs in Europe

Industrial sector	numbers	Flux [m³/d]
Automobile	1	225
Chemical Industry	15	70 – 1,360
Leachate	48	10 – 18,000
Food Industry	9	100 – 1,840
Tannery	5	40 - 800
Composting	2	40 – 50
Cosmetics	3	120 - 680
Malthouse	2	100
Paper	1	900
Pharmaceutical Ind.	15	50 – 1,500
Ships/ Cruisers	15	10 - 740
Tank cleaning	3	200
Textile Industry	5	10 –1,440
Rendering plants	4	40 - 960

COMMENTS AND EXPERIENCES

Pre treatment

The wastewater needs to be carefully pre treated before entering the MBR plant. It is advisable to remove abrasive or sharp edged materials which can hurt the membranes as well as fibers or hairs which can clog the membrane (modules) and lead to a dramatic and rapid decrease of the flux. Screens or even better sieves with mesh sizes < 0.5 mm have proved suitable. Further a grease trap should be installed, because oil and grease may influence the flux of the membranes negatively.

The hydraulic equalisation is of importance, because the membrane surface has to be designed according to the maximum inflow. Thus a storage and equalisation tank to cut the peaks is advisable.

Aeration Tank

Design and operation

The use of membranes to separate the biomass leads to some changes in the design and operation of the aeration tank. As already mentioned, the MLSS in MBRs can be raised to usually about 10 to 15 g/L. As the aeration tank is designed based on the load (F/M-ratio), higher MLSS and similar F/M as in conventional activated sludge plants, translates in smaller aeration tank volumes. Operational experience shows that MBRs can be simulated by the activated sludge model (ASM 1 and ASM3 by IWA). Thus in principal the biodegradation of organic compounds doesn't differ from conventional plants.

In principal two borderline cases of design and operation are possible:

- Small aeration tanks at the same F/M-ratio and similar surplus sludge production as in conventional ASPs

- Operation at extreme long sludge ages, i.e. very low F/M-ratio, minimizing the amount of surplus sludge but maximum of specific oxygen consumption thus high energy demands

There is no operation mode to get both positive effects, low energy consumption and zero sludge production rates.

Sludge characteristics and oxygen transfer

The sludge characteristic differs from conventional activated sludge, mainly due to the higher MLSS. The sludge viscosity increases with increasing MLSS. The viscosity of the MBR sludge is non-Newtonic i.e. it decreases at higher shear stress.

The higher viscosity may lead to a lower α-value (= ratio of the aeration coefficient k_La under process condition to the clean water transfer coefficient) which is about 0.6 at MLSS of 12 g/L compared to 0.8 at conventional ASP at MLSS of 3 to 5 g/L.

Energy Consumption

The specific energy demand of municipal membrane bioreactors is higher compared to conventional treatment plants. At the municipal MBR in Markranstädt (Germany) the energy consumption is reported to be about 1 kWh per m^3 inflow (Stein et al., 2001). Whereby the "crossflow" aeration is main energy consumer with about 0.7 kWh/m^3. In Rödingen (Germany) the membranes are installed in an external filtration tank, thus the energy demand is higher due to additional recirculation. The overall energy demand is reported to be about 2.0 kWh per m^3 inflow (Drensla, 2001) (mechanical treatment 0.6 kWh/m^3, biological station 0.35 kWh/m^3, filtration Unit 0.86 kWh/m^3, whereby the "crossflow" aeration consumes about 0.5 kWh/m^3, rest 0.2 kWh/m^3). Anyhow, it has to be considered that the plant was not optimised yet in respect of energy consumption.

Membrane Cleaning

The membranes require regular cleaning. It has to be distinguished between different cleaning procedures, as f. e.

- backwash with permeate
  (depending on the membrane/module type every few minutes)
- chemical enhanced backwash (e.g. daily)
- maintenance cleaning (e.g. weekly)
  e.g. NaOCl 13% - 500 ppm Cl, cleaning with water, Citric acid (0,5%) at pH 2.5 to 3, cleaning with water
- intensive cleaning (1-2 times per year) outside MBR
  e.g. with citric acid and NaOCl 1000 ppm at 35 °C

Frequency as well as type and concentration of chemicals depend strongly on wastewater composition, membrane and module type and are not standardized so far. In contrast, cleaning strategies are a focus of research with regard to avoid the use of chlorinated products (AOX-formation !) and to reduce the so called "aging" of membranes caused by the use of oxidizing chemicals.

Lifetime of Membranes

There are little reliable information about the lifetime of membranes. Although some are in operation since 5 to 6 years without failures respective with annual replacements of less than 3% [Churchhouse et al., 2003], others had to be replaced after 2 to 3 years because of serious fouling or even mechanical destruction. One can assume that lifetime is strongly correlated with the composition and pre treatment of the waste water, the applied cleaning strategies of the membrane modules, as well as with the type of membrane and module construction.

ENERGY CONSUMPTION

The specific energy demand of municipal membrane bioreactors (MBRs) is reported to be higher compared to conventional treatment plants.
The higher demand is due to additional energy consumers as the generation of the crossflow and as already mentioned a lower α-value. The α-values where reported in a wide range of 0.2 to 0.7 and discussed pretty controversial [Guender, 1999; Rosenberger et al., 2000; Cornel et al., 2002]. To quantify the α-values in full scale plants, oxygen transfer tests were performed in two municipal MBRs (Rödingen and Markranstädt, Germany). Further the oxygen transfer efficiency (OTE) and the standard aeration efficiency (SAE) were evaluated. In parallel to the oxygen transfer tests under process conditions, the viscosity of the sludge at different MLSS was determined.
Viscosity tests were performed using a rotating viscometer with a concentric cylinder measuring system. Thereby a rpm (revolutions per minute) is set and the system measures the shear stress and the viscosity in dependence of the angular velocity. In Figure 3 the viscosity at different shear stresses is shown.

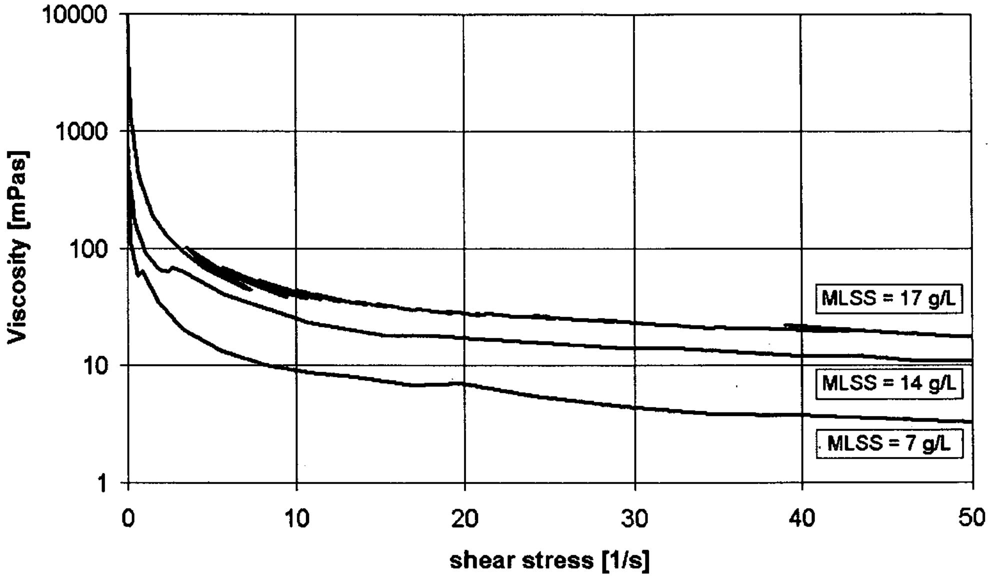

Figure 3: Viscosity vs. shear stress of MBR sludge at different MLSS concentrations

It can be seen that the viscosity decreases at increasing shear stress. Further the Figure shows an increasing viscosity at increasing MLSS concentration. Due to the non-Newtonic dynamic behaviour of the MBR sludge it is compulsory to give both shear stress and viscosity. Guender (1999) calculated from the bubble velocity a representative viscosity at a shear stress of 40 1/s.

The oxygen transfer tests in the two plants with fine bubble aeration system were performed with the absorption method. The oxygen transfer rate (OTR) [kg/h] is an absolute rate. A better comparable parameter is the oxygen transfer efficiency (OTE) [%/m]. The OTE in MBR#1 (Markranstädt) ranges from about 2.1 %/m to 4.3 %/m under process conditions at MLSS from 7 g/L to 17 g/L. Thus the oxygen transfer and therewith the OTE depends on the MLSS content. A similar result was obtained in MBR#2 (Rödingen). The OTE in clean water was estimated as 8.5 %/m, in mixed liquor the OTE decreased from 3.7 %/m to 2.8 %/m at increasing MLSS from 9.5 g/L to 14 g/L. At both municipal MBRs the OTE is in the same order of magnitude. In Figure 4 the OTE of both MBRs is depicted, including the standard deviations.

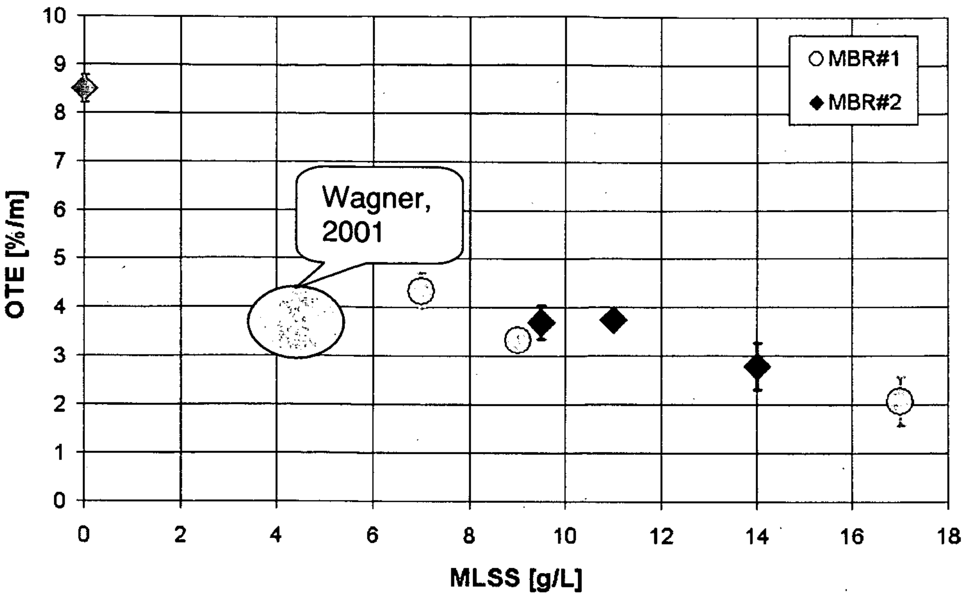

Figure 4: Oxygen transfer efficiencies of fine bubble aeration systems

Wagner [2001] analysed more than 300 treatment plants with respect to OTE-values. Compared to his results the measured OTEs correspond to a common fine bubble aeration system.

Oxygen transfer tests with the additional "crossflow" aeration system 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 in value compared to the fine bubble aeration system. Figure 5 shows a comparison of the volumetric OTR of both aeration systems in the MBR Markranstädt.

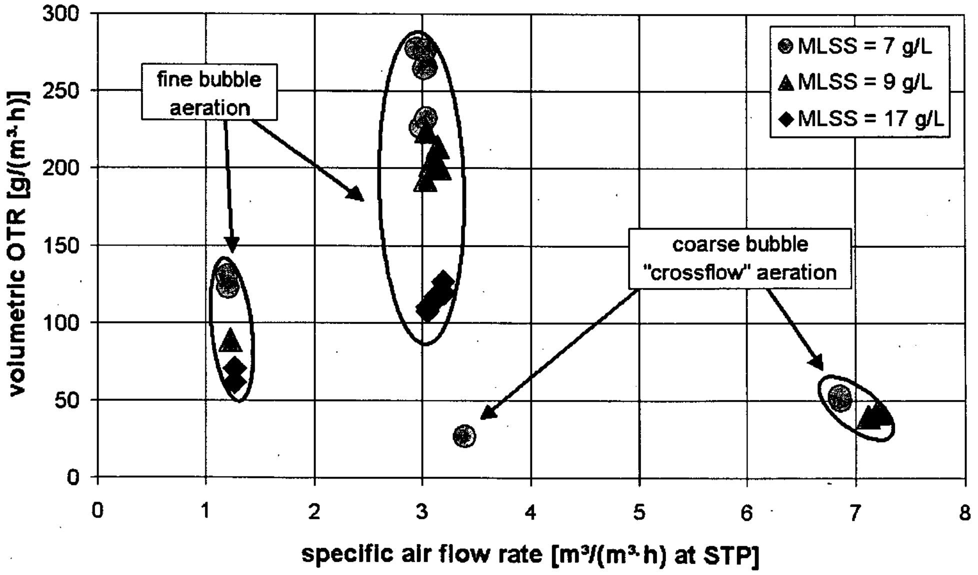

Figure 5: Comparison of volumetric OTR of both aeration systems (STP = standard temperature and pressure)

In evidence the OTR of the fine bubble aeration is much higher at less air flow. Otherwise, as 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 6). At MLSS of 7 kg/m³ 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 m³/(m³·h) at STP.

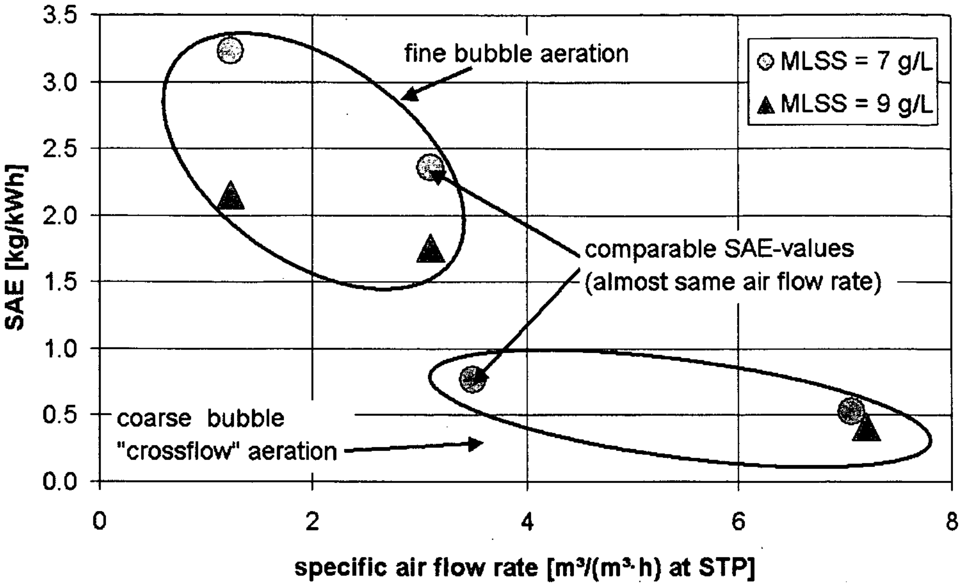

Figure 6: Aeration efficiency of both aeration systems

The α-value is defined as the ratio of the volumetric transfer coefficient under process condition (field k_La_{f20}) to the clean water transfer coefficient (k_La_{20}) according to following equation:

$$\alpha = \frac{k_La_{f20}}{k_La_{20}} \quad [-]$$

Due to this definition all influences regarding to the oxygen transfer are considered. For determination of the α-value it's compulsory to calculate the ratio at the same airflow rate and other conditions like depth of submergence.

Calculated mean α-values can only be depict in ranges. The ranges in Rödingen (MBR #2) result from the application of the off-gas method (variations in k_La and OTR in time). In Markranstädt (MBR #1) the ranges are larger because the clean water tests were performed under different hydraulic conditions compared to the tests under process conditions (absence of membranes in the clean water tests). Figure 7 depicts the average α-values in dependence of MLSS for the two full scale MBRs. Measurements between 7 and 17 kg/m³ MLSS concentration were performed. The average α-values in this range are between 0.7 and 0.4 respectively.

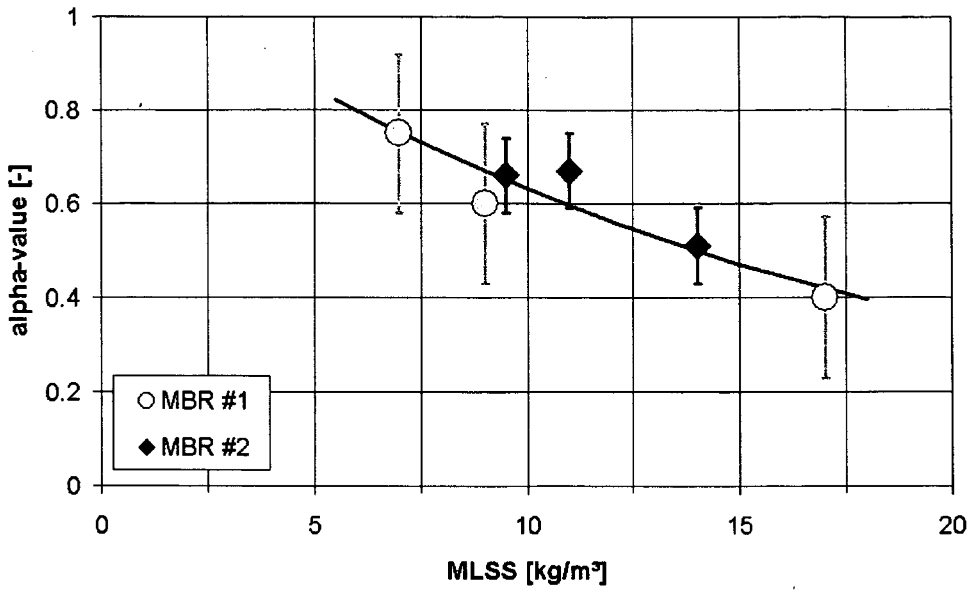

Figure 7: α-values in dependence of MLSS concentration for both municipal MBRs

Nevertheless a good correlation between α-value and MLSS concentration can be seen. Because of the measurements of the viscosity the α-values also can be depict in dependence of viscosity. In Figure 8 the average α-values vs. viscosity is shown.

According to Günder [1999] in Figure 8 the representative viscosity at shear stress of 40 1/s is used. It can be seen that the correlation between α-value and viscosity is in even better accordance as the correlation of α-value and MLSS concentration.

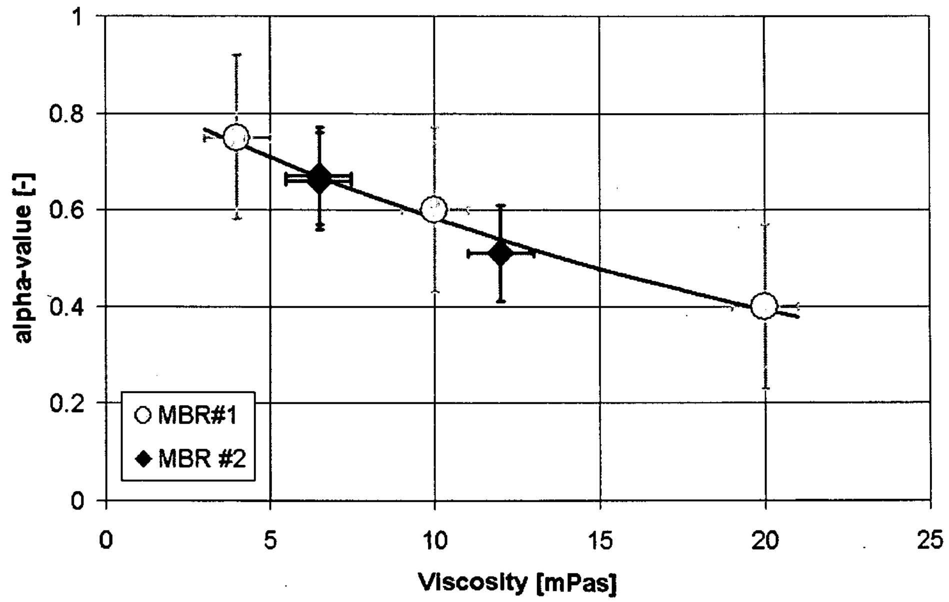

Figure 8: α-values vs. viscosity (at 40 1/s shear stress) for both municipal MBRs

CONCLUSIONS

About 30 municipal and more than 120 MBRs in industry are installed in Europe. Small footprints and high effluent quality free of suspended solids and basically free of pathogenic germs are the main objectives.

Disadvantageous is the higher energy consumption by a factor of 2 to 3 compared to conventional activated sludge plants. The overall energy demand of submerged systems is reported to be 1.0 to 1.5 (2.0) kWh per m^3 treated water. 2/3 of the energy in municipal MBRs is needed to generate the crossflow to control the fouling.

The α-value of fine bubble aeration systems in municipal full scale MBRs at 12 kg/m^3 MLSS is about 0.6 (± 0.1), thus comparable to conventional municipal WWTPs at lower MLSS and lower sludge age but about 0.2 units lower as in conventional stabilization plants.

There are little information about the lifetime of membranes. Although some are in operation since 5 to 6 years almost without failures, others had to be replaced after 2 to 3 years because of serious fouling or mechanical destruction. One can assume that lifetime is strongly correlated with the composition and pre treatment of the waste water, the applied cleaning strategies of the membrane modules, as well as with the type of membrane and module construction.

Oxygen transfer tests of fine bubble aeration systems at different MLSS indicate a dependence of α-value and MLSS. At decreasing MLSS increasing α-values are observed. This might be caused by the higher viscosity of the MBR sludge.

The standard aeration efficiency (SAE) of the "crossflow" aeration system for fouling control is about three times lower than the fine bubble aeration system which provides oxygen supply. Thus for limitation of energy consumption the "crossflow" aeration should be used for fouling control only.

The measured results regarding the α-value show that MBRs represent an alternative solution to conventional WWTPs in wastewater treatment. The energy consumption for oxygen supply in municipal MBRs is due to the measurements in full scale MBRs in the same order of magnitude as municipal conventional WWTPs. However the energy for the generation of the crossflow (for fouling control) is for the total energy consumption of higher importance.

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