VATTEN 63:69–78. Lund 2007

TWO YEARS OF EXPERIENCE WITH SEMI-TECHNICAL SCALE MEMBRANE BIOREACTOR (MBR)

Två års erfarenheter med biologisk membranreaktor (MBR) i halvteknisk skala

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Abstract

In wastewater treatment applications the MBR technology combines biological treatment and a membrane system to provide organic and suspended solids removal. Installation of low-pressure membranes within a biological reactor system replaces sedimentation, screening and media filtration as means of separating mixed liquor suspended solids (MLSS) from treated wastewater. This study is focused on experiments with ZeeWeed10™ MBR (Zenon GmbH) installed at the outlet of the main process line at Himmerfjärden WWTP, situated in Grödinge (south of Stockholm, Sweden). Results obtained for the MBR tests showed effluent water quality improvement in comparison with the full-scale plant performance with efficiency from 12 % removal efficiency for total nitrogen to 100 % for MLSS. Additionally, Design of Experiments methodology (Modde 7), was applied for evaluation of fouling phenomenon in order to optimize the ZeeWeed10™ operation. 35 l m^{-2} h^{-1} of flux and 7 minutes filtration with 40s of backwash were found as the optimal effective permeation conditions for the MBR process. The permeation fouling rate (PFR) was chosen as the major criterion that illustrates the membrane fouling occurrence and shows the necessity for membrane cleaning procedure. Furthermore, the comparative studies of two membrane units (ZW_{500} and ZW_{NEW}) were completed with an emphasis on fouling occurrence and indicated the ZW_{NEW} as more fouling-resistant.

Key words – designing of experiments (DOE), fouling phenomenon, membrane bioreactor (MBR), wastewater

Sammanfattning

Användning av biologiska bioreaktorer (MBR) kombinerar vid avloppsvattenrening biologisk behandling med membransystem för att avlägsna organiskt och partikulärt material. Vid installering av låg-trycks membran inom ett biologiskt reningssystem ges möjligheter att ersätta sedimentering, silning och filter för att separera suspenderat material (MLSS) från utgående behandlat avloppsvatten. Denna studie inriktades emellertid på användning av ZeeWeed10™ MBR (Zenon GmbH) som slutsteg vid Himmerfjärdens avloppsverk beläget i Grödinge söder om Stockholm. Erhållna resultat med MBR visade på en förbättrad reningseffekt varierande från 12 % för totalt kväve till 100 % för suspenderat material. För att utvärdera igensättning av membran i samband med optimering av driftparametrar användes programmet Modde 7 (Design of Experiments). Bästa genomströmningsbetingelser på 35 l m^{-2} h^{-1} för MBR erhölls vid 7 minuters filtreringstid och backspolning på 40 s. Hastigheten för igensättning valdes som huvudsakligt kriterium för att beskriva förekomst av igensättning och påvisar nödvändigheten av att rengöra membranen. Två jämförande studier av igensättning genomfördes med två olika membranenheter (ZW_{500} och Zw_{NY}) och indikerade att ZW_{NY} var mer motståndskraftigt mot igensättning.

Introduction

In research and commercial applications the membrane bioreactor (MBR) system is gaining an increasing attention, especially where a high quality of water is required and the wastewater treatment process is focused on improving the treatment technology. Those systems are capable of releasing product of high quality from the sources that were never considered before, such as wastewater and brackish water. The recycling of wastewater has become possible and it has been applied in places where water resources are limited and with water scarcity. The immersed membrane bioreactor system (MBR) is a unique wastewater treatment process designed for numerous municipal and industrial applications (Stephenson et al., 2000; Le-Clech et al., 2006; Yang et al., 2006). As presented in Table 1, the MBR system has many features that makes it competitive to the conventional wastewater treatment and gives an opportunity to produce superior effluent quality.

Despite that there are many scientific papers already published worldwide and hundreds of full-scale MBR systems are in operation, the membrane technology challenges further analysis and research. Mainly it is focused on optimization of process performance, elimination the fouling phenomenon and improvement of physical-chemical properties of materials for membranes. Firstly, development of techniques eliminating fouling phenomenon that is affecting the MBR performance are surely under investigation around the world . Clogging of pores within membrane surface by the solid matter that results in diminishing the process efficiency is a general problem that occurs during membrane process performance. It could be mainly observed in case of submerged membrane bioreactors operation with very highly contaminated liquors having total solids concentration of 20 g l^{-1} or more arising from concentrated biomass (Judd, 2005). Different types of interruptions distinguished in filtration process that are observed in the macro- and micro-scale during MBR operation are named generally as fouling phenomenon. Physical fouling, caused by colloidal species, occurs as the plugging of membrane surface. Inorganic and organic fouling, respectively, usually refer to scalants and macromolecular species. Organic fouling in MBRs has been studied and characterised in the same way as has biological fouling. It has been estimated that almost half of all fouling deposits in membrane systems comprise or involve biofilms (Judd, 2004). For reducing the fouling, combination of different strategies like reducing the flux, increasing the membrane aeration and employing physical or chemical cleaning are practically used. Prevention of fouling could also be accomplished by modifying the membrane hydrophilicity, operating the membrane with non-fouling conditions by improving the aeration, modifying the SRT, sustainable flux and biomass suspension pre-treatment (Le-Clech et al., 2006).

After 10 years of research it has not been precisely defined which of main factors influence mostly the fouling phenomenon occurrence since it is individual for every MBR plant with different composition of wastewater. Lee et al. (2002) focused on developing the mathematical model for the submerged membrane bioreactor (SMBR) that combines the activated sludge model with

Table 1. *Different aspects concerning MBR technology (modified after van der Roest et al., 2002 and Stephenson et al., 2000).*

Advantages	Disadvantages
Effluent quality:	
– complete solids removal from effluent	
– effluent disinfection-bacteriophage concentration in an MBR permeate is 100–1000 times lower than in the WWTP effluent	
– combined COD, solids and nutrient removal	
Effectiveness:	
– efficient removal in a single unit	– membrane fouling affect the process efficiency
– high loading rate capability	
Plant operation:	
– small footprint/limited space requirements	– costs of membranes and maintenance (energy for pumping, aeration)
– no problem with sludge bulking	
– low sludge production (loading rates ~ 0.01 COD kg^{-1} MLSS)	– less efficient oxygen transfer caused by high MLSS concentrations
– flexible extension of existing WWTP	
– secondary clarifiers and effluent filters can be eliminated	– cleaning procedure – usage of cleaning chemicals may cause a toxic shock on the biological system
– processes are easily automated; operator requirements are reduced	

a membrane fouling model. Model simulation investigated in this study showed that the soluble microbial products (SMP) formation is closely related with not only biological kinetic parameters but also operating parameters such as sludge retention time (SRT) and food to microorganisms ratio (F/M). It has been found that fouling is considerably depended on the biological factors such as SMP, TSS, SRT and F/M ratio. Studies performed by Kimura et al. (2005) showed that depending on the F/M ratio, the membrane foulant tends to change. Combination of off-site chemical cleaning and fine air aeration could minimize fouling occurrence in submerged MBR (Sofia et al., 2004). Other investigation also confirms that cleaning protocol is also a major issue that should be carefully designed for every MBR system (Le-Clech et al., 2006).

In this study a semi-technical scale MBR operation was conducted at the end of treatment process in full-scale at Himmerfjärden municipal WWTP. The municipal WWTP is situated in southwestern part of Stockholm and serves 250 000 persons and industry connections as equivalent to 35 000 PE. Treatment process includes ferrous sulphate precipitation, nitrification with activated sludge, post denitrification with external methanol and ethanol and sand filtration as the last step. The aim of this unique location of MBR was to develop a biomass culture that would improve the removal process of the residual of organic compounds that pass the treatment process (Snowball Project). In this paper, mainly the operational conditions with application of Design of Experiments (DOE) with Modde 7 program were found and evaluated (Eriksson et al., 2001). Special attention was focused on fouling phenomenon in ZeeWeed10™ and possibilities for reducing the factors that affect the process efficiency.

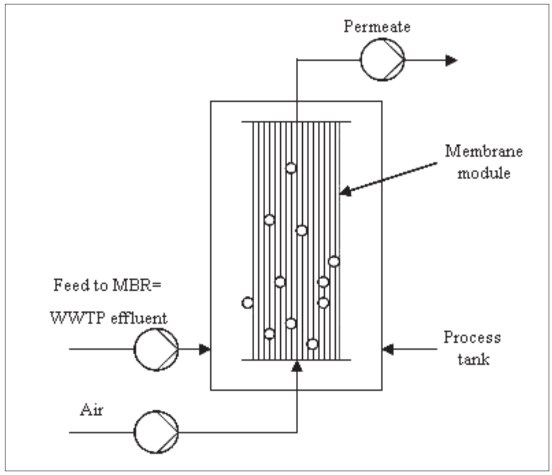

Figure 1. *Configuration of membrane bioreactor ZeeWeed10™.*

Materials and methods

Semi-technical pilot plant ZeeWeed10™

The ZeeWeed10™ ultrafiltration membrane pilot plant was constructed by Zenon GmbH and installed at Himmerfjärden WWTP in Grödinge in September 2004 at the end of treatment process. The configuration of MBR is presented in Figure 1. The ZeeWeed10™ consists of elements like: process tank (0.07 m^3), membrane unit, backwash tank (0.04 m^3), cabinet with control panel, reject/effluent pump (process pump) and blower and is continuously supplied with effluent from the Himmerfjärden WWTP. The semi-technical scale plant is a compact membrane ultrafiltration system that can be used to generate preliminary performance data prior to further evaluation or pilot scale testing. Analysis of wastewater samples and observations of biomass growth were conducted and compared to full-scale plant. Furthermore, two membrane units made of different materials were studied and compared by means of clogging occurrence onto membrane surface. Overall, the experience of two years operational period has been combined in order to describe and illustrate the membrane bioreactor performance as a new technology for wastewater treatment applications.

Membrane module

ZeeWeed module was equipped with ZW-500 Type (Zenon GmbH) outside/in hollow fibre membrane manufactured of PVDF with nominal diameter of fibre 1.9 mm (internal 0.9 mm) and pore size 40 nm and 0.93 m^2 of the nominal surface area. At the end of 2005 a new module received from Zenon for testing replaced the hollow fiber membrane unit. The difference between the old one and the new one is the material and chemical properties – new one was made of more fouling resistant material. A partial vacuum inside hollow fibres created by a pump ensured the outside-in filtration system. Continuous aeration of the unit kept the fibres moving and created a flow along the membrane surface. Operational parameters like TMP ranging from 0.12–0.70 bar and flux from 20–40 l m^{-2} h^{-1} were applied, depending on the operational period. During membrane operation the backwash flush was designed after every 7^{th}–10^{th} minute of filtration and lasted 20–60 seconds. The chemical cleaning was able to restore the permeability of the membranes more than two times and decrease the pressure about two times.

Cleaning procedures

The membrane performance was strictly limited by occurrence of fouling phenomenon that affects on process efficiency, decreases flux and requires higher pressure to maintain designed flux. Two types of cleaning are used for membrane maintenance: chemical cleaning and backwash cleaning. Chemical cleaning was performed by membrane soaking in cleaning chemicals such as sodium hypochloride (concentration range 500–1000 ppm) and citric acid (2–5 g l^{-1}), respectively (for the ZeeWeed10™ pilot plant according to the Cleaning In Place, CIP, procedure delivered by Zenon GmbH). Backwash cleaning is based on reverse flow with filtrate. Membrane uses clean filtrate to backwash itself according to the time filtration cycles set automatically by operators.

Analysis of wastewater and biomass

The concentration of mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) for sludge was determined. Preliminary oxygen uptake rates (OUR) were conducted occasionally in order to check the biomass respiratory activity in MBR according to the procedure described in another studies (Długołęcka et al., 2006). The chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) was analyzed regularly in the influent and effluent from the MBR plant with standard vial tests of DrLange. Total organic carbon (TOC) was analyzed with application of online TOC meter at WWTP. The characteristics of activated sludge in 2005 is presented in the Table 2. Analysis of wastewater was scheduled once a week during 2005 when the ZW_{500} was operated, while in 2006 after installation of ZW_{NEW}, the influent and effluent samples were analyzed once a month.

Table 2. *MBR – activated sludge characteristics, average values 2005 (Niedziołek, 2005).*

Parameter	Value
Influent flow	0.72 $m^3\ d^{-1}$
Temperature	13–20 °C
Biological loading	0.126 kg COD $kgMLSS^{-1}\ d^{-1}$
Sludge concentration	1.278 kg MLSS m^{-3}
Sludge production	1.774 kg MLSS d^{-1}
SVI*	138 ml g^{-1}

*SVI – Sludge Volume Index

Designing of MBR operational parameters

Calculation procedure

ZeeWeed10™ pilot plant was connected to the computer system at WWTP. TMP and flow rates were recorded and stored as average values for every minute of operational time. Stored data were analyzed and finally calculated (ZENON TechNote 01-47). Main calculations were done to describe the membrane operational parameters, Eq. 1–4 (van der Roest et al., 2002). Fouling phenomenon could be presented as the difference in Trans Membrane Pressure (TMP) before and after backwash and it shows the recovery of the membrane permeation (Eq. 4). However, for longer time periods, permeation fouling rate is the most reliable parameter that refers to decrease in TMP as a function of time (Eq. 3).

- **flux** – the flow of liquid through the membrane surface

$$F = Q \cdot A^{-1}\ \ [\mathrm{l\ m^{-2}\ h^{-1}}] \qquad \text{Eq 1.}$$

Where:
Q – flow of permeate [$l\ h^{-1}$]
A – membrane surface [m^2]

- **permeability** – the flux for a particular pressure drop

$$Permeability = flux \cdot TMP^{-1}\ \ [\mathrm{l\ m^{-2}\ h^{-1}\ bar^{-1}}] \qquad \text{Eq 2.}$$

Where:
TMP – trans-membrane pressure [bar]

- **permeation fouling rate**

$$\textit{Permeation fouling rate} = \textit{difference between } TMP \cdot day^{-1}\ \ [\mathrm{bar\ day^{-1}}] \qquad \text{Eq 3.}$$

Where:
difference between TMP – at the beginning and end of the calculated time period

- **Delta P**

$$Delta\ P = TMP_{BB} - TMP_{AB}\ \ [\mathrm{bar}] \qquad \text{Eq 4.}$$

Where:
TMP_{BB} – before backwash
TMP_{AB} – after backwash

Modde 7

Umetrics package includes Modde 7 program that creates and evaluates statistical experiments. Design of Experiments (DOE) was applied for planning and performing the representative experiments in order to obtain the optimal conditions for membrane pilot plant operation. DOE is an efficient approach for organizing

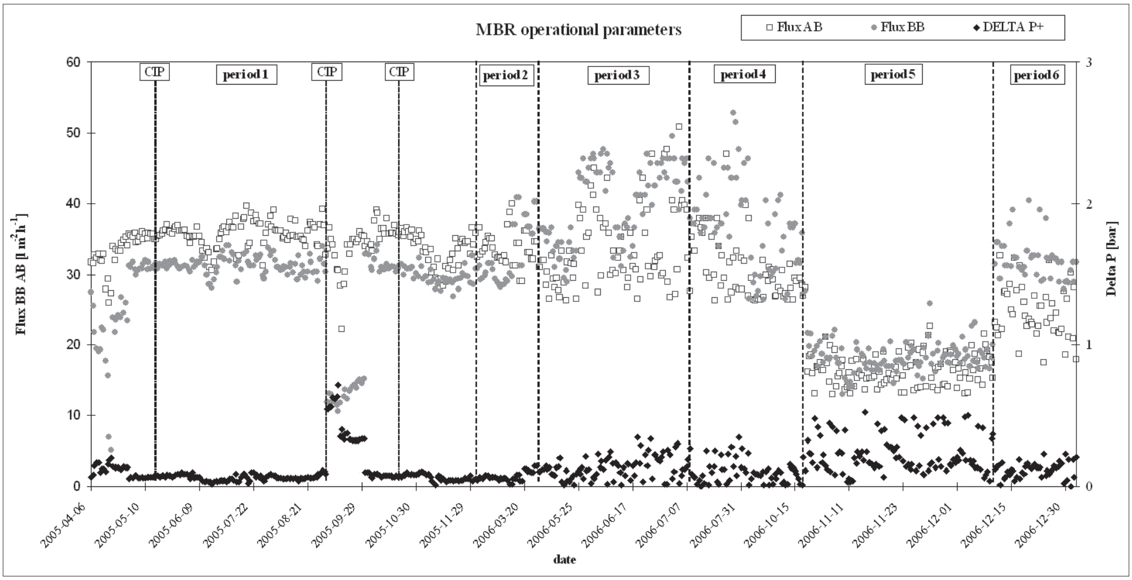

Figure 2. *Operational parameters of membrane pilot ZeeWeed10™, (CIP-cleaning in place, BB – before backwash, AB-after backwash).*

experimental work. Modde 7 generated as few experiments as possible and the selected experiments were maximally informative. Each experiment was designed with different values of flux, time of filtration and backwash. Final results were calculated as permeability fouling rate and selected as response variables. Acquired data was analyzed by regression analyses and the model relating the changes in the factors to the changes in the responses have been obtained for each experimental period (Eriksson et al., 2001). Results from modeling were coupled into response contour plots that clearly illustrated the optimal operating conditions. Furthermore, the result generated a model showing the importance of all factors and their interactions. The short 8h test with different fluxes and filtration time were performed in 2005 for ZW_{500}. Thereafter, in 2006 similar tests designed by Modde 7 were lengthen to the 6 days and conducted for a new membrane module ZW_{NEW}.

Results and discussion

The ZeeWeed10™ pilot plant was in operation for two years with some technical failures that are described in the following section. Concerning the different experimental trials and operational conditions the results are divided in six periods, as presented in Figure 2. In Table 3 operation parameters are calculated. Modde7 was used for optimization experiments in order to define which combination of important factors will result in optimal operating conditions for ZeeWeed10™.

MBR ZeeWeed10™ performance

After delivery of MBR to the wastewater treatment plant, the unit was supplied with process water for 8 weeks with a flux of 45 l m^{-2} h^{-1}. Next, the MBR was placed at the end of the treatment process and supplied

Table 3. *MBR – operating conditions.*

Period	Date	Membrane	HRT [h]	F [$lm^{-2}h^{-1}$]	Delta P [bar]
1	04.–11.2005	ZW_{500}	5	32.1	0.114
2	12.2005–03.2006	*ZW_{NEW}	5	32.1	0.062
3	04.–07.2006	*ZW_{NEW}	4.3	37.0	0.131
4	07.–10.2006	*ZW_{NEW}	4.8	33.7	0.099
5	11–12.2006	ZW_{500}	9.3	17.3	0.236
6	12.2006	*ZW_{NEW}	5.7	28.2	0.122

with effluent from the Himmerfjärden WWTP. The main goal was to build up a specific bacterial culture for removal of residues of pharmaceutically active compounds. The reactor with submerged membrane and the membrane surface was the special kind of 'catchers' for all the activated sludge flocs that were washed out from the treatment processes. During the first period (Fig. 2) the membrane was operated continuously with the constant flux of 32 l m^{-2} h^{-1}, which was assured by the cleaning procedures (CIP). Trans membrane pressure was ranging from 0.20 at the beginning of installation to 0.55 bar depending on the biofilms formation onto membrane surface and cleaning performance.

Due to the technical failure with magnetic valve, all cultivated activated sludge was lost and had before exceeded the value MLSS of 2.5 g l^{-1}. Thereafter, the reactor was seeded with activated sludge taken from the full-scale biological reactor and kept at a MLSS concentration up to 3 g l^{-1}. Simultaneously, Zenon GmbH delivered the new membrane unit ZW_{NEW} with hollow fibres made of new kind of material for testing. In the 2nd and 4th periods the new membrane was installed and operated at the flux of 32 l m^{-2} h^{-1}, while the pressure dropped to 0.12 bar at the beginning and up to 0.35 bar during the process performance. It appeared that with the new membrane module it was possible to obtain the designed flux with less energy and lower TMP (see Table 3).

Scattering of flux values and differential trans membrane pressure observed in the 3rd period was resulted from experimental trials designed by DOE with Modde 7 program. 11 test for 6 days each were generated and performed with different values of flux and filtration time (ZW_{NEW} module). The cleaning procedure carried out afterwards aimed at eliminating of the additional pore clogging of the membrane surface that took place during the experimental period. At the end of period 4, the cover of membrane unit was damaged. In order not to lose the activated sludge culture and keep the process in operation, the old membrane unit was installed. Because of the long time of exploitation of the old membrane and many experimental trials (short test with the landfill leachate wastewater in summer 2005; trials with high flow) the flux dropped to 17 l m^{-2} h^{-1} with the same and even higher than 0.6 bar value of trans membrane pressure. The high rate of clogging and low permeability through the membrane surface was observed. Thereby the efficiency of the filtration of MBR performance dropped significantly. After the new membrane unit was connected again in the period 6, a stable flux was achieved and amounted to 28 l m^{-2} h^{-1} with TMP 0.35 bar. It should be pointed out that the new membrane ZW_{NEW} could generate the stable flux value with the lower energy requirements in comparison to the ZW_{500}. However, a higher TMP difference was observed, although, the cleaning procedures were conducted more often when the ZW_{500} was in operation.

Biomass growth during MBR performance and additional analysis

Analysis results of MLSS and MLVSS concentration was the tool for observation of biomass growth in the membrane bioreactor. At the start up period, the microorganisms that were flowing in with the wastewater built the biomass flocs in MBR and no seeding took place at this stage. As presented in Figure 3, after almost one year of operation the MLSS concentration exceed a value of 2.5 g l^{-1}. Due to insufficient aeration equipment in the reactor tank that should assure proper mixing of the suspension, the recirculation of the settled sludge from the tank bottom was carried out manually a few times every week. At the beginning the MLSS concentration increased rapidly, while after some period the concentration was rather stable, fluctuating around the value of 1.5 g l^{-1}. After almost one year of operation, the 2.5 g l^{-1} MLSS concentration was achieved. No surplus sludge production was observed during the MBR process performance. Compared with studies performed by Rosenberger et al. (2002) with 535d of MBR operation as a replacing system for conventional biological process, the biomass concentration increased to much higher value and amounted to 18–20 g l^{-1}. It must be mentioned that MBR was supplied with WWTP effluent and it is a low grade nutrient medium for biomass growth. The optimal COD:TN:TP ratio for MBR process performance was estimated approximately to 100:11:1.9 (van der Roest et al., 2002, Wei et al. 2006), while in ZeeWeed10™ amounted to 100:25:1.1 with significantly lower content of nutrients. It should be pointed out that COD is not easily degradable at the WWTP effluent, what can be confirmed by the low removal rate in MBR, amounted to 16.2% in 2006 (Table 4).

In Figure 4 the results from TOC and COD analysis are presented. The feed water was characterized with the fluctuating values of COD and TOC respectively, while the MBR effluent demonstrated stable values of COD and TOC that amounted to 20±8.1 mg l^{-1} and 10±2.9 mg l^{-1}, respectively.

Activated sludge from membrane bioreactor was examined selectively 4 times in order to observe the oxygen consumption for bacterial groups present in MBR. According to the specific procedure described in earlier paper (Długołęcka et al., 2006), the oxygen uptake rates (OUR) were estimated for nitrifiers and heterotrophic bacteria respectively. Taking into consideration that the WWTP effluent was feed water for MBR, the oxygen

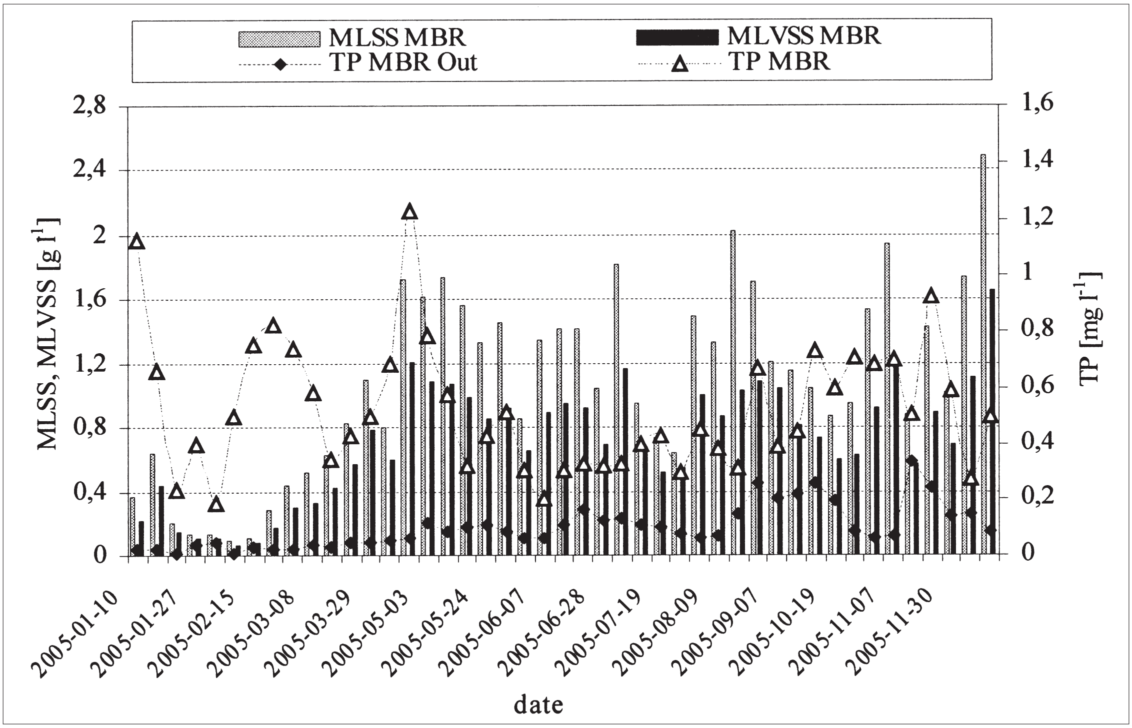

Figure 3. *Analysis of suspended solids and total phosphorus in MBR and effluent during 2005.*

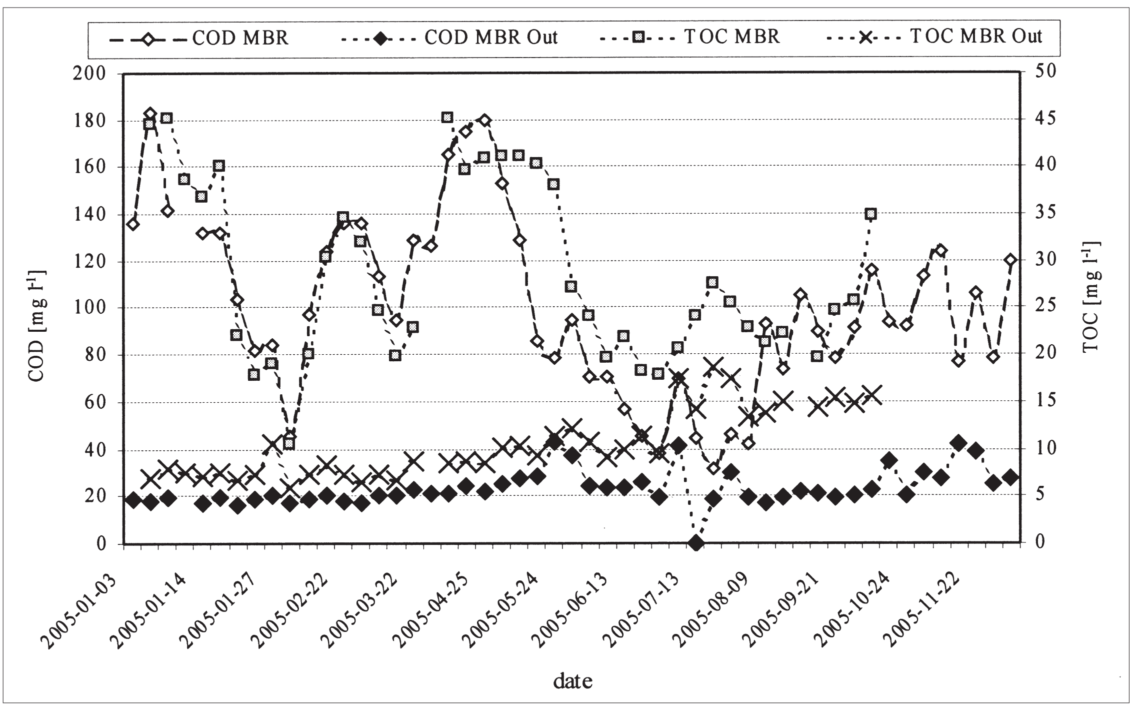

Figure 4. *COD and TOC values in analyzed samples from MBR and effluent during 2005.*

Table 4. *Average values from MBR and WWTP effluents.*

Analysis	2005			2006		
	WWTP	+MBR	Efficiency [%]	WWTP	+MBR	Efficiency [%]
COD	35	24	31.4	37	31	16.2
TOC	m.v.	10.6	m.v.	12	11.2	6.7
SS	9.2	0	100	12	0	100
TN	8.8	7.5	14.8	9.0	7.9	12.2
TP	0.39	0.10	74.4	0.49	0.17	65.3

m.v. – missing value

consumption for nitrifiers was calculated and amounted to 0.5 – 0.72 mg O_2 gMLVSS^{-1} h^{-1}. However, the respirometric activity of heterotrophic bacteria was significantly higher than observed in the previous bacterial group and was equal to 5.2 – 11.9 mg O_2 gMLVSS^{-1} h^{-1}. In comparison, the oxygen uptake rate (OUR) estimated in activated sludge from full scale aeration tanks were ranging from 8.1 to 18.9 mg O_2 gMLVSS^{-1} h^{-1} for nitrifiers and 19.4 – 35.4 for heterotrophic bacteria. The differences in the oxygen consumption of biomass in MBR and full-scale aeration tank could be explained by the different characteristics of the feed water and thereby different sludge composition.

At the end of December 2005 the activated sludge was lost due to the magnetic valve failure. Thereafter the seeding sludge was taken from the full-scale aeration reactor and diluted in order to obtain the MLSS concentration around 2.5–3.0 g l^{-1} and kept at the same level. During 2006 the activated sludge samples were taken regularly for batch test performance with pharmaceutically active compounds (article in preparation). Analyses of wastewater samples were performed monthly and are presented together with results from 2005 in Table 4. The summary of those analyses indicates the better wastewater quality with application of MBR connected to the technological process. Especially the concentration of MLSS was reduced by 100 %, and a significant decrease in TP concentration could be observed.

Design of experiments (DOE) with membrane pilot plant operational parameters

Different parameters such as flux, filtration cycle with the backwash time was taken under consideration as factors that have major influence on fouling phenomenon. Design of Experiment (DOE) program generated 17 experimental designs with different variable factors for performing the 8 hour tests in the Period 1 (Niedziołek, 2005). Permeation fouling rate is the parameter that could clearly illustrate the fouling occurrence during membrane performance. However, in this case the differences between PFR in the following test were not significant due to the short duration of the tests. Still, the TMP differences before and after the backwash (Delta P between 0.008–0.02), revealed that fouling can be minimized by operation with optimized time of 10 minutes of filtration and time of 40 s of backwash. In the meantime, to maintain flux at stable level is the key factor of the permeation. It turned out that the length of backwash time was not the main parameter influencing the fouling and it can be reduced from 60 to 20 seconds. However, the omission of backwash after each filtration cycle is highly not recommended.

By lengthening the time of designed test performed in 2006, the calculated permeation fouling rate as the function of time could reflect the real membrane bioreactor performance and show the fouling occurrence (Fronczyk, 2006). In the Figure 5, an example of contour plot generated by Modde 7 is presented and shows the filtration time together with flux values plotted with estimated responses of PFR. Analyzing this optimization curves it is possible to choose the most suitable parameters for membrane operation depending on the process expectations. For semi-technical MBR at this site of technological process, the most efficient flux is 35 l m^{-2} h^{-1} with filtration time 7 minutes and the PFR exceeds the value of 0.001 bar day^{-1}.

The comparison of operation of two membrane units, ZW_{500} and ZW_{NEW} was performed. Results were compared taking into account the fouling phenomenon occurrence during operational experience of two membrane modules. ZW_{500} module operated in 2005 is made of polyvinylidene fluoride (PVDF) and was later exchanged to ZW_{NEW} made of new kind of fouling-resistant material. During the selection of the period for comparative studies, variable changes due to experimen-

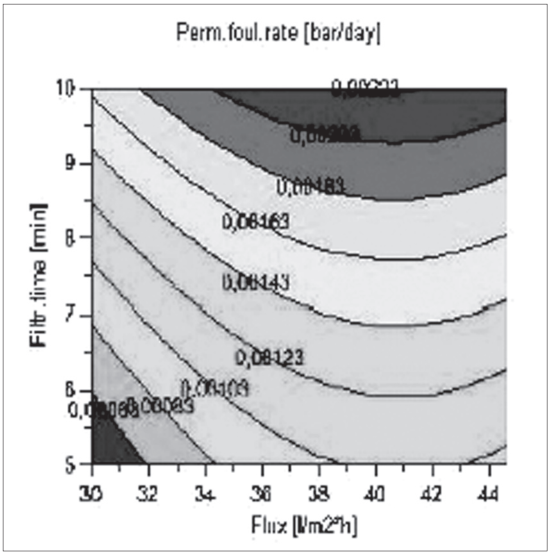

Figure 5. *Contour plot for optimization of MBR ZeeWeed10™$_{NEW}$ (Fronczyk, 2006).*

tal periods with Modde7 and operational designs were taken into account. The periods with similar operating conditions for each membrane module were distinguished, calculated according to the similar procedure and compared (see Table 5). As it could be observed for both membranes the flux value was designed in the range of 35–37 l m^{-2} h^{-1}. A greater recovery of membrane permeability after backwash was observed for the ZW$_{500}$ than for ZW$_{NEW}$ module. However, the PFR estimated during the compared periods was six times lower for the ZW$_{NEW}$ module (0.0011) than for ZW$_{500}$ (0.0068), even if the Delta P value was comparable to ZW$_{500}$. It could indicate that Delta P, which reflects the instantaneous difference in TMP before and after backwash, does not reflect the real fouling occurrence on the membranes surface in the long run.

Conclusions

- The membrane bioreactor system could achieve a long solids retention time and the biomass could be completely retained. Thereby, no SS concentration detected in the effluent water. Concerning the MBR system as the process replacing the conventional activated sludge process in a biological step of full scale wastewater treatment process, secondary clarifiers and effluent filters can be eliminated.
- COD, TOC, MLSS, TP and TN analysis showed a higher quality of MBR effluent water in comparison with Himmerfjärden WWTP.
- Application of Umetrics software with Design of Experiments program (Modde 7) gave successful results concerning the optimization of operational parameters for the semi technical scale MBR; flux amounted to 35 l m^{-2} h^{-1} and 7 minutes of filtration time.
- Cleaning procedures performed with sodium hypochloride and acidic acid every 4 months were satisfactory for the effective recovery of membrane permeability.
- Taking into account the fouling phenomenon occurrence, the permeation fouling rate as a function of time was recognized as the most representative calculation that could reflect the membrane performance capacity.
- Comparative studies on two membrane units, ZW$_{500}$ and ZW$_{NEW}$, made of different materials indicated a higher fouling resistance of ZW$_{NEW}$, with permeation fouling rate calculations as a main criterion illustrating fouling occurrence.

Acknowledgements

Financial support obtained from SYVAB, Swedish Institute and Lars Erik Lundbergs Stipendiestiftelse is acknowledged. Authors are thankful to Bengt Hultman for advice and comments. The authors wish to thank Jan

Table 5. *Fouling occurrence of two membrane modules – comparison of parameters (based on Fronczyk, 2006).*

Period / Membrane	FluxAB [l m^{-2} h^{-1}]	FluxBB [l m^{-2} h^{-1}]	DeltaP [bar]	PFR [bar day^{-1}]
2005 / ZW$_{500}$	35.4	31.2	0.0708	0.0068
2006 / ZW$_{NEW}$	35.2	30.3	0.0613	0.0011
2005 / ZW$_{500}$	37.01	31.9	0.0675	0.0062
2006 / ZW$_{NEW}$	36.2	30.1	0.1487	0.0018

Flux AB – after backwash, Flux BB – before backwash

Bosander for all help with the project. Great appreciation goes to all employees at SYVAB who help with pilot plant operation: Stor Tack! Appreciation goes also to master students Małgorzata Niedziołek and Wojtek Fronczyk for help in the experimental part. Support from Ulrich Mende from Zenon GmbH is also acknowledged.

Nomenclature

COD – Chemical Oxygen Demand, [mg l^{-1}]
HRT – hydraulic retention time, [h]
SRT – sludge retention time, [day]
MLSS – mixed liquor suspended solids concentration, [g MLSSl^{-1}]
MLVSS – mixed liquor volatile suspended solids concentration, [g MLVSS l^{-1}]
TSS – Total Suspended Solids [g SS l^{-1}]
TN – total nitrogen concentration, [mg l^{-1}]
TP – total phosphorus concentration, [mg l^{-1}]
SMP – soluble microbial products
WWTP – wastewater treatment plant
(S)MBR – (submerge) membrane bioreactor
ZW_{500} – membrane unit, Type ZeeWeed 500 (Zenon GmbH)
ZW_{NEW} – new membrane unit, delivered by Zenon GmbH for testing (specification not available)
TMP – trans membrane pressure, [bar]
F – flux, the flow of liquid through the membrane surface area, [l m^{-2} h^{-1}]
Permeate – effluent from membrane bioreactor installation
Permeability – a measure of membrane performance (flux per unit of TMP)
PFR – permeation fouling rate, [Δbar day^{-1}]
CIP – cleaning in place – recovery cleaning with chemicals

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