Performances and fouling control of a flat sheet membrane in a MBR pilot-plant

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ABSTRACT

This paper deals with the performance and the optimisation of the hydraulic operating conditions of the A3 Water Solutions flat sheet membrane technology in a MBR pilot-plant to achieve a satisfying fouling control and also a reduction in the required aeration. Two vertically stacked modules were tested at pilot-scale at Anjou Recherche under typical biological operating conditions (mixed liquor suspended solids concentration (MLSS) = 10 g/l; sludge retention time (SRT) = 28 days; food to microorganism ratio (F/M) = 0.12 kg COD/kg MLSS/d). The use of a double-deck and of specific backwashes for this membrane technology enabled to achieve satisfying membrane performances for a net flux of 25 L h^{-1} m^{-2}, 20°C at a low specific aeration demand per membrane surface (SADm = 0.2 Nm^3 h^{-1} m^{-2}) which corresponds to a specific aeration demand per permeate volume unit (SADp) of 8 Nm^3 air/m^3 permeate, which is lower than reported for many commercial membrane systems. The mixed liquor characteristics (foaming, MLSS concentration) appeared to influence the fouling behaviour of the membranes but no correlation was found with the fouling rate. However, with the new operating conditions, the system is robust and can cope with fouling resulting from biological stress and daily peak flows for MLSS concentrations in the membrane tank up to 18 g/l.

Key words | backwash, double-deck, flat sheet membrane, membrane bioreactor

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INTRODUCTION

Membrane bioreactors (MBR) are increasingly employed in wastewater treatment due to increased local water scarcity, the need for wastewater reuse (50–70% of the wastewater will be reused in 2012 in the Middle East) and more stringent wastewater regulations. They present many benefits over conventional processes such as their advanced effluent quality, the possibility of reuse (e.g for irrigation), the increased volume of organic loading and reduced plant footprint. The first generation of membrane bioreactors were operated with organic or inorganic tubular membranes placed in external recirculation loops. Immersed bioreactors were developed in the middle of the 1980 s based on an idea of Yamamoto *et al.* (1989) in order to simplify the use of these systems and reduce operating costs. In this configuration, membranes are directly immersed in the tank containing the biological mixed liquor and permeate water is extracted. During the last ten years, many public and industrial research projects were undertaken enabling an important decrease of MBR costs by optimising the membrane technologies themselves (Sridang *et al.* 2005), the biological treatment (Chang & Lee 1998) and the hydraulic operating conditions (Wu *et al.* 2008). This contributed to the development of the MBRs throughout the world: in 2005, about 300 references of industrial applications (>20 m^3/d) and about 100 municipal wastewater treatment plants (>500 population equivalent) in Europe were listed (Lesjean & Huisjes 2008). MBR systems are expected to show further increase in capacity and

doi: 10.2166/wst.2010.127

expand their range of applications. Larger MBRs are already in construction or planned such as the plant of Brightwater, USA (143 800 m^3/day), planned for 2011.

However, the membrane fouling control remains a limiting phenomenon and requires the use of air scouring which is responsible for the main operating costs. In spite of recent developments to improve the module design (Sridang *et al.* 2005) and air distribution into the module (Nguyen Cong Duc *et al.* 2008), the stacking of the modules (Judd 2005), and the use of the intermittent aeration (Fane 2005); the energy costs for an MBR are still higher than a conventional activated sludge process. Further optimisation and cost reduction is required. Optimum filtration parameters like flux, relaxation (Hong *et al.* 2002), backwash time and frequency (Schoeberl *et al.* 2005) for each technology must be found to achieve a satisfying membrane fouling control and at the same time reduce the membrane aeration intensity for maximum water productivity: maximum net flux must be reached to obtain the lowest specific aeration demand per membrane surface (SADm) and per permeate volume unit (SADp). Current membrane systems are now able to operate at a net flux of 20–25 $L\,h^{-1}\,m^{-2}$ for SADm values ranging from 0.2 to 0.8 $Nm^3\,h^{-1}\,m^{-2}$ and SADp values ranging from 10 to 25 Nm^3air/m^3 permeate (Judd 2006, 2007; Garcès *et al.* 2007).

Within the framework of the AMEDEUS project, new membrane technologies were developed and optimised at pilot-scale. This paper deals in particular with the performance and optimisation of the hydraulic parameters of a MBR pilot using A3 Water Solutions flat sheet system to achieve a reliable control of the fouling and reduce operating costs.

MATERIALS AND METHODS

The performances of the A3 Water Solutions technology were evaluated and optimised for 1 year in a pilot plant shown in Figure 1 at Anjou Recherche, the Research Centre of Veolia Water. The pilot was fed by municipal wastewater from the town of Maisons Laffitte (France) by a pump after screening through a 1 mm drum screen. The mean feed water characteristics are given in Table 1.

The pilot unit was composed of a biological tank (1.6 m^3 of sludge), a membrane tank (2.6 m^3 of sludge) and a permeate tank as shown in Figure 1. The wastewater was fed at the bottom of the biological tank intermittently aerated with fine bubbles and agitated with an impeller to ensure nitrification and denitrification. Mixed liquor was pumped from the biological tank to the membrane tank. The latter consisted of an aerated tank in which two

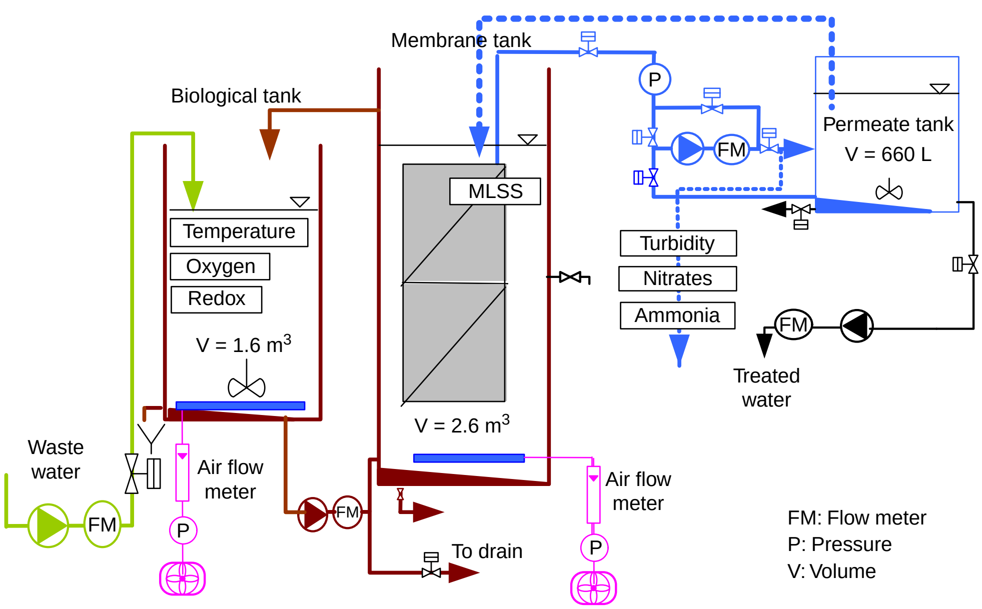

Figure 1 | Pilot plant configuration.

Table 1 | Wastewater characteristics

Parameter	TSS (mg/l)	COD (mg/l)	TN (mg/l)	TP (mg/l)	Total coliforms (nb/100 ml)
Feed water	170 ± 60 (191 samples)	515 ± 165 (210 samples)	59 ± 14 (204 samples)	9 ± 2 (81 samples)	$144.10^5 \pm 133.10^5$ (15 samples)

A3 Water Solutions vertically stacked modules ($2 \times 70\,m^2$) were immersed. A pump was used to extract the permeate water from the membrane. It was collected in a storage tank and was partly re-circulated to the membrane tank to ensure a defined hydraulic retention time (HRT). The concentrated mixed liquor overflowed back to the biological tank.

The biological operating conditions, typical of MBR systems (Table 2) were maintained constant during all trials in order to consider only the influence of the hydraulic operating conditions on the fouling behaviour of the membrane. Some variations occurred especially with foaming events which led to mixed liquor losses and at the end of the trials when the mixed liquor suspended solids (MLSS) concentration in the membrane tank was voluntary increased by reducing the sludge volume and decreasing the mixed liquor recirculation rate.

The A3 membrane filtration concept is based on a block of flat sheet, made of PVDF with a pore size of 0.2 μm. The module is built with multiple filtration plates arranged in parallel, evenly distributed. The membrane cushions are fixed by moulded sides, in which the filtrate is collected as shown in Figure 2. The modules (1 m high) can be easily stacked on top of each other to form double- or triple-decker stacks. Filtration occurs from outside to inside of the plates. To ensure maximum filtration efficiency, an aeration ramp with medium-size bubbles is installed below the filtration module stack. The resulting turbulence in the gas-liquid mixture ascending through the spaces between the individual membrane plates enables the filtration cake deposits to detach. The filtration process operates in the so-called filtration/pause. A backwash procedure was also developed for this type of module.

The hydraulic membrane performances (trans-membrane pressure, filtration flow rate, temperature), the quality of the permeate water (ammonia and nitrate concentrations) and the characteristics of the sludge (MLSS concentration, oxidation-reduction potential (ORP), oxygen concentration) were monitored with a data acquisition system. The permeability, calculated using Darcy law, and the flux are always reported at 20°C in this paper.

Wastewater and permeate water analyses (total suspended solids (TSS), chemical oxygen demand (COD), total nitrogen (TN), ammonia ($N\text{-}NH_4^+$), total phosphorus (TP), pH…) were performed daily to evaluate the treatment performances of the pilot unit. The bacteriological quality of the permeate water was checked every month (coliforms counting according to NF EN ISO 9308-1). The mixed liquor characteristics (MLSS, COD in the supernatant, Capillary Suction Time (CST), viscosity for a shear gradient of $1{,}200\,s^{-1}$, polysaccharides in supernatant (Dubois method), proteins in supernatant (BCA kit) were analyzed weekly in order to see if membrane fouling could be due to biological stress.

RESULTS AND DISCUSSION

Biological performances

The quality of the treated water throughout the trials is given in Table 3. The biological treatment performed according to expectations within the MBR, even during

Table 2 | Biological operating conditions

Biological operating conditions	MLSS (g/l)	SRT (d)	F/M ratio (kg COD/kg MLSS/d)	Volumetric load (kg COD/m^3/d)	HRT (h)
Mean values	9.7 ± 2.4 (210 samples)	28 ± 2 (200 samples)	0.12 ± 0.04 (143 samples)	1.36 ± 0.42 (185 samples)	8.3 ± 1.8 (299 samples)

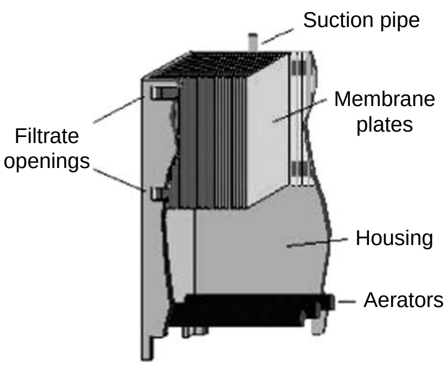

Figure 2 | A3 Water Solutions technology.

biological disruptions, with a total removal of the suspended solids, a COD concentration always less than 70 mg/l and a total coliform removal of 6 log (Table 3). The membrane acted therefore as a physical barrier to remove the suspended solids and the turbid matter. The average total nitrogen removal rate was only around 55% because the pilot was not designed to optimise the nitrification/denitrification process.

Control of the fouling

The first months of trials enabled the operating conditions of the A3 Water Solutions technology to optimize. A3 Water Solutions usually recommended operating with a net filtration flux of 15 $L h^{-1} m^{-2}$, filtration/relaxation cycles of 8 min/2 min and at a SADm of 0.7 $Nm^3 h^{-1} m^{-2}$ for a simple deck (Table 4). At the beginning of the trials, the pilot operated with these standard conditions of A3 Water Solutions except for the aeration. As a double-deck was installed in the pilot-plant instead of a simple-deck, the SADm was divided by two and fixed at 0.34 $Nm^3 h^{-1} m^{-2}$. Moreover, maintenance cleanings were performed every two weeks.

The net permeate flux was first gradually increased and it appeared that the membrane permeability stabilized at around 550 $L h^{-1} m^{-2} bar^{-1}$ for a net flux of 26 $L h^{-1} m^{-2}$ which corresponded to a SADp of 12 Nm^3/m^3permeate (part 1 of Figure 3). To reduce further the energetic cost due to membrane aeration, the SADm was decreased from 0.34 to 0.20 $Nm^3 h^{-1} m^{-2}$ which led to permeability decrease (part 2 of Figure 3). To maintain the permeability, daily backwashes were then carried out which resulted in the permeability stabilisation over 4 next weeks for a net flux of 25 $L h^{-1} m^{-2}$ (part 3 of Figure 3). To ensure that this permeability stabilisation was due to the use of backwashes, they were stopped again (parts 4, 5 and 6 in Figure 3) and a new decrease of the permeability was observed. Then, a sharp permeability decrease occurred due to sludge foaming. To minimise the foaming intensity, the membrane air, the feed and permeate flow rates were simultaneously decreased (part 5 in Figure 3). After the foaming event, operating at a net flux of 26 $L h^{-1} m^{-2}$ gave a low permeability of 250–300 $L h^{-1} m^{-2} bar^{-1}$. To recover the membrane permeability, 4 maintenance cleanings were performed successively, but it did not lead to a stabilisation of the permeability (part 6 in Figure 3). Daily backwashes and weekly maintenance cleanings were then performed and they allowed a progressive recovery of the permeability with a stabilisation in the range of 400 to 500 $L h^{-1} m^{-2} bar^{-1}$ (part 7 in Figure 3).

The fouling behaviour of the system was then studied when performing peak flows and increasing the MLSS concentration in the membrane tank. The pilot plant, still operating with a net flux of 25 $L h^{-1} m^{-2}$, a SADm of 0.2 $Nm^3 h^{-1} m^{-2}$ and peak flows (equal to 1.5 times the net flux of 25 $L h^{-1} m^{-2}$ keeping a SADm of 0.2 $Nm^3 h^{-1} m^{-2}$) were programmed to occur twice a day during two hours. One backwash was carried out after one of the peak flows. A decrease of the permeability was observed during the peak flows (Figure 4) but after, it recovered to its original value. No loss of the membrane permeability was observed at the beginning of the peak flow tests until a new sludge

Table 3 | Treated water quality

Parameter	TSS (mg/l)	COD (mg/l)	TN (mg/l)	TP (mg/l)	Total coliforms (nb/100 ml)
Treated water	0	16 ± 6 (210 samples)	26 ± 8 (194 samples)	6 ± 1.6 (80 samples)	14 ± 9.8 (15 samples)
Mean removal rate	100%	96.6%	54%	31%	6.9 log

Table 4 | Original and new operating conditions of the A3 Water Solutions system

	Original operating conditions	New operating conditions
Module configuration	Simple-deck	Double-deck
Membrane footprint (m^2 membrane/m^2 floor area)	133	266 (multiplied by 2)
Net flux ($L\,h^{-1}\,m^{-2}$)	15	25 (multiplied by 1.67)
SADm ($Nm^3\,h^{-1}\,m^{-2}$)	0.7	0.2 (divided by 3.5)
SADp (Nm^3/m^3 permeate)	47	8 (divided by 5.9)
Membrane aeration	Continuous	Continuous
Filtration cycle (filtration/relaxation)	8 min/2 min	8 min/2 min
Cleaning strategy	Intensive cleanings with chlorine	Daily backwashes + weekly maintenance cleanings
Max MLSS in the membrane tank	–	18 g/l
Peak flows	–	2 peak flows of 2 h at a net flux of 40 $L\,h^{-1}\,m^{-2}$

foaming event occurred which led to a permeability drop, similar to the one observed in Figure 3. The use of backwash and maintenance cleanings avoided a rapid fouling, although the peak flows still occurred, and then the recovery and stabilisation of the permeability when the quality of the mixed liquor quality improved (Figure 4). The established hydraulic operating conditions enabled it to cope with the fouling due to foaming event and the peak flows.

At the end of the trials, the MLSS concentration was voluntary increased in the membrane tank by reducing the sludge volume in the biological tank and the mixed liquor recirculation flow rate. Results highlighted that the membrane permeability dropped above a MLSS concentration of 18 g/l in the membrane tank. Therefore, the system can operate safely at a net flux of 25 $L\,h^{-1}\,m^{-2}$ at a SADm of 0.2 $Nm^3\,h^{-1}\,m^{-2}$ with MLSS concentrations in the membrane tank up to 18 g/l. Compared with the original design

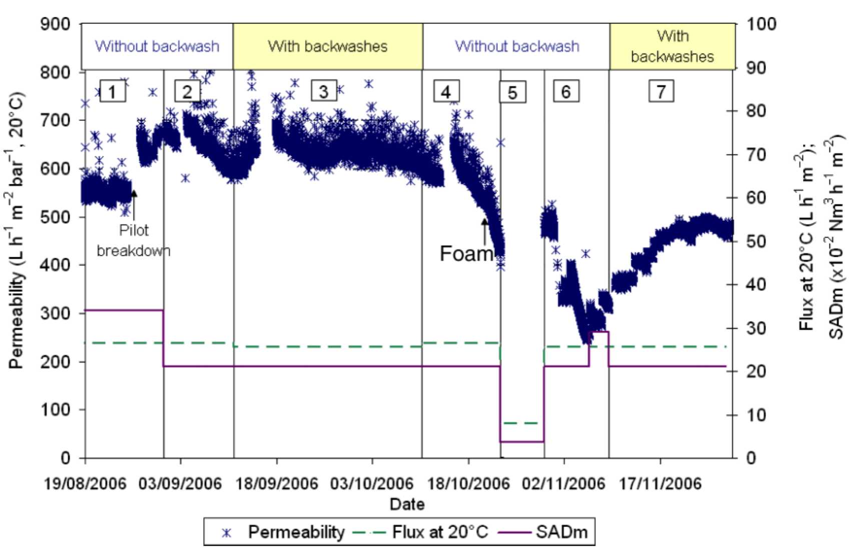

Figure 3 | Comparison of the operation with and without backwashes.

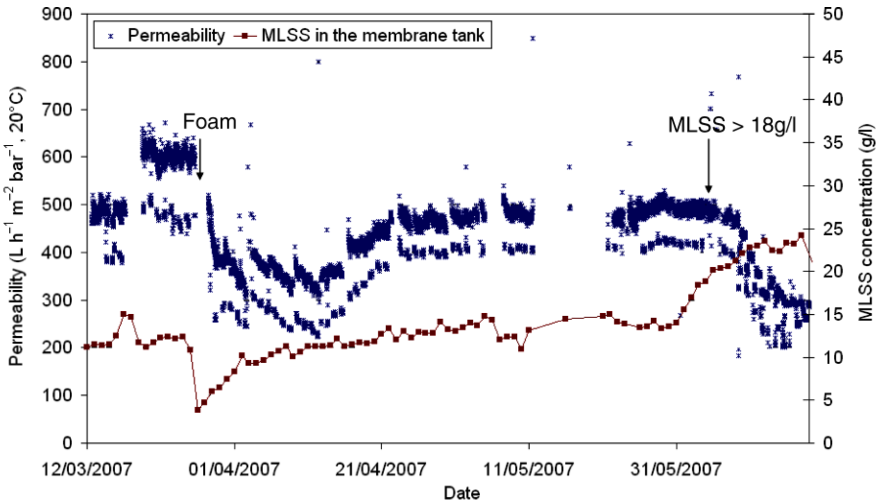

Figure 4 | Operation at a net flux of 25 L h^{-1} m^{-2} for a SADm of 0.2 Nm^3 h^{-1} m^{-2} with peak flows and MLSS concentration from 4 to 24 g/l.

of A3 Water Solutions, this was a reduction of the membrane air flow per cubic metre of permeate of 80% (Table 4), which relates to important energy savings.

The results highlighted in addition that the membrane performances were also greatly related to the quality of the mixed liquor in particular the foam formation and the MLSS concentration as reported by several publications (Choi *et al.* 2002; Rosenberger *et al.* 2005; Meng *et al.* 2007). However, no correlations were for instance found between the wastewater, mixed liquor characteristics and the biological operating conditions with the fouling rates maybe because of the complex interactions in the system. A statistical analysis is currently in progress to identify other influencing factors on the fouling behaviour of the membrane. The fouling due to biological stress remains difficult to foresee and having a robust system that can cope with this type of fouling is essential.

Impact of the double-deck

The use of the double-deck enabled the aeration demand to decrease because the air bubbles were used to clean more membrane surface (Judd 2005). However, the increase of the membrane height can induce higher MLSS concentration and pressure gradient differences along the membrane. To analyse the influence of the double-deck on the fouling, the permeability of each module (top and bottom) was measured once per week as shown in Figure 5.

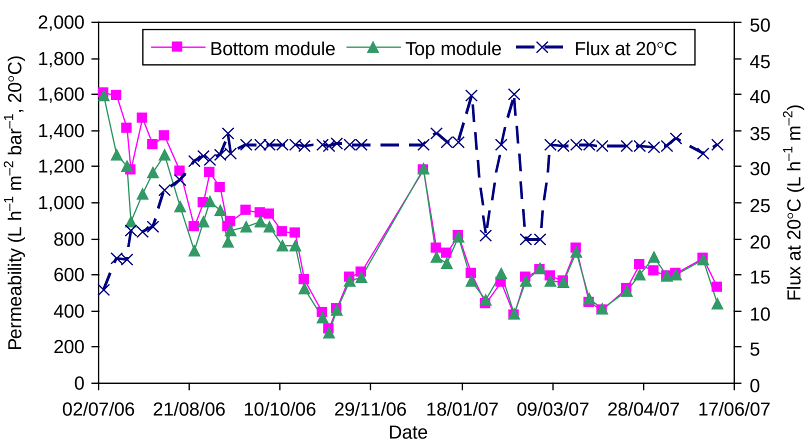

Figure 5 | Evolution of the permeability of each module.

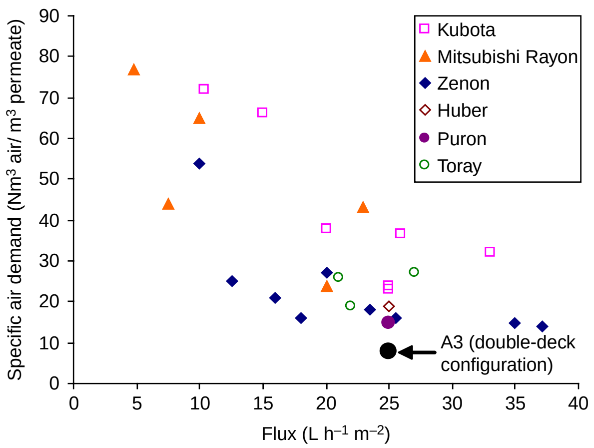

Figure 6 | SADp in function of the net flux for various MBR plants (Judd 2007) and the pilot unit of Anjou Recherche, using A3 Water Solutions technology.

Both modules followed a similar fouling pattern. Therefore, the double-deck configuration did not affect the membrane performances and is a good way to decrease the membrane aeration demand for flat sheet membranes. Also, triple-deck could be interesting to decrease the aeration demand further.

Performances of the membranes of A3 Water Solutions and from current market leaders

Most of the current commercial membrane systems are now able to operate at a net flux of 20–25 $L h^{-1} m^{-2}$ for relatively low aeration demand according to pilot and full-scale data (SADm values from 0.2 to 0.8 $Nm^3 h^{-1} m^{-2}$ and SADp values from 10 to 25 Nm^3air/m^3 permeate) (Judd 2006, 2007; Garcès *et al.* 2007). The new developed operation mode of the A3 Water Solutions technology outperformed these values from current market leaders presenting SADp higher than 10 Nm^3 air/m^3 permeate (Judd 2007) (Figure 6). The aeration demand can probably still be further decreased by using triple-deck configuration.

CONCLUSIONS

The development of a new operation mode including the use of double-deck configuration and specific backwashes for flat sheet membranes enabled the achievement of membrane performance for the A3 Water Solutions technology which outperformed the current market leaders. Indeed, it was shown that the system could operate in a pilot plant under typical biological operating conditions (MLSS = 10 g/l, SRT = 28 d, F/M = 0.12 kg COD kg $MLSS^{-1} d^{-1}$ at a net flux of 25 $L h^{-1} m^{-2}$ for a low SADm of 0.2 $Nm^3 h^{-1} m^{-2}$ which corresponds to a SADp (8 Nm^3 air/m^3 permeate) lower than the ones reported for current membrane systems for pilot or full-scale plants. Moreover, the system can support fouling due to peak flows and biological stress with these operating conditions for MLSS concentration in the membrane tank up to 18 g/l. The quality of the sludge appeared to influence greatly the membrane performance but no correlations appeared between the mixed liquor characteristics and the fouling rates revealing the complexity of the system. A robust system is therefore essential to cope with unexpected events.

This paper shows that it is possible with a reliable filtration system and adapted filtration conditions to achieve a satisfying fouling control when using low membrane air flow rates. Further developments of the filtration system designs and new cleaning strategies adapted to each system should permit a reduction in the operating costs of the MBRs.

ACKNOWLEDGEMENTS

The work reported in this article was developed within the EU FP6 project AMEDEUS (contract no. 018328). The authors would like to acknowledge the European Commission for the financial support.

REFERENCES

Chang, I. S. & 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**(3), 221–233.

Choi, J. G., Bae, T.-H., Kim, J.-H., Tak, T.-M. & Randall, A. A. 2002 The behaviour of membrane fouling initiation on the crossflow membrane bioreactor system. *J. Memb. Sci.* **203**(1–2), 103–113.

Fane, A. G. 2005 Towards sustainability in membrane processes for water and wastewater processing. *Proceedings: International congress on Membranes and Membrane Processes (ICOM)*, August 21–26, Seoul, Korea.

Garcès, A., De Wilde, W., Thoeye, C. & De Gueldre, G. 2007 Operational cost optimisation of MBR Schilde. *Proceedings: IWA 4th International Membrane Technologies Conference*, May 15–17 Harrogate, UK.

Hong, S. P., Bae, T. H., Tak, T. M., Hong, S. & Randall, A. 2002 Fouling control in activated sludge submerged hollow fiber membrane bioreactors. *Desalination* **143**(3), 219–228.

Judd, S. 2005 Fouling control in submerged membrane bioreactors. *Water Sci. Technol.* **51**(6–7), 27–34.

Judd, S. 2006 *The MBR Book: Principles and Applications of Membrane Bioreactors in Water and Wastewater Treatment*. Elsevier, Oxford, UK.

Judd, S. 2007 Membrane bioreactors: state of the art. *Proceedings: AWA Membrane Speciality Conference II*, February 21–23, Melbourne.

Lesjean, B. & Huisjes, E. H. 2008 Survey of European MBR market: trends and perspectives. *Desalination* **231**(1–3), 71–81.

Meng, F., Shi, B., Yang, F. & Zhang, H. 2007 New insights into membrane fouling in submerged membrane bioreactor based on rheology and hydrodynamics concepts. *J. Memb. Sci.* **302**(1–2), 87–94.

Nguyen Cong Duc, E., Fournier, L., Levecq, C., Lesjean, B., Grelier, P. & Tazi-Pain, A. 2008 Local hydrodynamic investigation of the aeration in a submerged hollow fibre membranes cassette. *J. Memb. Sci.* **321**(2), 264–271.

Rosenberger, S., Evenblij, H., Te Poele, S., Wingtens, T. & Laabs, C. 2005 The importance of liquid phase analyses to understand fouling in membrane assisted activated sludge processes-six case studies of different European research groups. *J. Memb. Sci.* **263**(1–2), 113–126.

Schoeberl, P., Brik, M., Bertoni, M., Braun, R. & Fuchs, W. 2005 Optimization of operational parameters for a submerged membrane bioreactor treating dyehouse wastewater. *Sep. Purif. Technol.* **44**, 61–68.

Sridang, P. C., Heran, M. & Grasmick, A. 2005 Influence of module configuration and hydrodynamics in water clarification by immersed membrane systems. *Water Sci. Technol.* **51**(6–7), 135–142.

Wu, J., Le-Clech, P., Stuetz, R., Fane, A. G. & Chen, V. 2008 Effects of relaxation and backwashing conditions on fouling in membrane bioreactor. *J. Memb. Sci.* **324**(1–2), 26–32.

Yamamoto, K., Hiasa, M., Mahmood, T. & Masuo, T. 1989 Direct solid-liquid separation using hollow fiber membrane in an activated-sludge aeration tank. *Water Sci. Technol.* **21**, 43–44.