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Long-term operation of a full scale intermittent MBR

F. Fatone[1], P. Battistoni[2], P. Pavan[3], F. Cecchi[1]
[1]Department of Science and Technology, University of Verona – Strada Le Grazie 15, Cà Vignal, 37134 Verona – Italy E-mail: fatone@sci.univr.it
[2]Institute of Hydraulics and Transportation Infrastructures, Marche Polytechnic University – Via Brecce Bianche, 60131 Ancona - Italy
[3]Department of Environmental Sciences, University of Venice "Cà Foscari"- Italy

The paper describes a real example of municipal wastewater treatment and reuse by a membrane bioreactor combined with the alternate cycles process. Focusing mainly on the membrane system, almost every detail of the first year operation regarding loading, membrane cleaning, long-term behaviour, fouling control and power consumptions has been analyzed in details. Long-term operation was carried out with permeate flux of 26 LMH, solid concentration in the membrane tank of 8÷11 g L^{-1} and specific aeration for membrane scouring in the range 0,12÷0,19 Nm^3 m^{-2} h^{-1}. The membranes were routinely cleaned in place once a week with hypochlorite solution (300 mgCl L^{-1}), and this practice seemed to play a key role for a good control of the membrane fouling. The membrane permeability was in the range 230÷240 LMH bar^{-1}.The system suffered from short-term loading peaks, on the contrary was able to face well the long-term seasonal fluctuations. The automatic control of the aeration and the operating strategy for the biological process contributed to power requirements in the range 0.44÷0.57 kWh m^{-3}.

1. Introduction

Membrane bioreactors (MBRs) can no longer be considered a novel technology and their widespread application for municipal wastewater treatment is likely expected. In spite of the full scale diffusion of these systems, the most appropriate practice to design and operate these systems is not consolidated (Judd, 2006). As for the Italian scenario, to date the two largest operating municipal MBRs are located in Brescia (1580 m^3 h^{-1}) and in Viareggio (250 m^3 h^{-1}) (Battistoni *et al.*,2006). Both come from the up-grading of existing plants and adopt submerged modules of ultrafiltration (UF) hollow fibre membranes. However, while the first is widely known because has been the largest in the world for few years, the second is more recent and less known, but may be considered very interesting because its biological process is intermittent, continuously fed and automatically controlled on the basis of on-line signals. This promising coupling of process control automation and membrane separation has been described in recent papers (Fatone *et al.*, 2005, 2006), which pointed out the possibility to achieve directly the water reuse for non-potable purposes.
This paper pays further attention to the Viareggio MBR, here focusing mainly on the membrane section. Both ordinary operation and singular short term events have been analyzed in details, so to better understand the real long-term behaviour of the advanced treatment system. In particular, it was investigated the effect of parameters that: (a) can be directly manipulated by the operators (i.e.: specific aeration demand for membrane scouring, operating net flux, cleaning protocol); (b) depend on the nature of the feed

(i.e.: long term seasonal fluctuations and irregular peaks of the inloadings); (c) change consequently to the before mentioned reasons (i.e.: change of sludge sedimentation characteristics). Finally, in order to evaluate the industrial sustainability of the operation and maintenance (O&M) of this type of systems, the real specific costs coming from power requirements and chemicals purchase are reported.

2. Materials and methods

2.1 The plant

In the Viareggio wastewater treatment plant (WWTP) the alternate cycles (AC) tank comes from the retrofitting of the pre-existing primary longitudinal clarifier (Reaction volume = 2200 m^3). Later, the ultrafiltration section was constructed after this intermittent bioreactor, so to finally obtain a membrane bioreactor operating the alternate cycles process (AC-MBR). To support the MBR with the suitable head-works, new pre-treatments (fine sieve and degritting in vortex chamber) and an off-line equalization basin were built. Figure 1 shows the simplified block flow diagram of the AC-MBR plant and the focus on the membrane section.

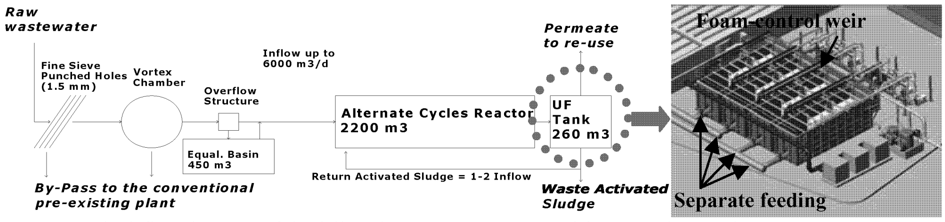

Figure 1. Block flow diagram of the full scale AC-MBR system and focus on the membrane section

As for the ultra-filtration (UF) section, the membrane tank is equipped with eight Zenon cassettes (total membrane area 12128 m^2) disposed in four parallel and hydraulically separated lines. Basically the UF section was engineered according to the usual practice for ZeeWeed hollow fibres submerged membranes, with coarse aeration at the bottom of the modules for the membrane scouring. Moreover, the tank was provided with a continuous weir to prevent from accumulation of foam and floating materials. The membranes were routinely cleaned in place and line by line, so to avoid the interruption of the filtration process. The maintenance cleanings were done once a week and consisted of a cycles of backwashing with hypochlorite at 300 mgCl L^{-1} (back flux of 30 LMH) and relaxation. Each cleaning operation incurred 40÷50 minutes.

2.2 The automatic control of the biological process

The alternate cycles (AC) is basically a bending point based control strategy on the basis of the redox potential (ORP) or dissolved oxygen (DO) on-line signals (Battistoni *et al.*; 2003). Aeration for the biological process is switched off when the ammonia break point is detected, and is switched on when the nitrate knee is detected. In this way the lengths of the aerobic and anoxic phases are controlled to be just sufficient for complete nitrification and denitrification, respectively. Moreover, the AC control algorithm includes also secondary branches, which are setpoint based and are necessary to safeguard the system in case the bending point based control may be not optimal.

3. Results and discussion

3.1. Factors influencing activated sludge filterability in municipal MBRs

Basically, the main factors that influence the filtration performance in MBRs may be associated to: (1) pre-treatments; (2) nature of feed to the membranes and activated sludge process; (3) hydrodynamic environment imposed to the membrane separation process (Judd, 2006). Further, each of the aforementioned facets depends on boundary conditions and parameters that can be manipulated.

Operating with MBRs, poor pre-treatment may: (1) build-up of trash, hair and fibrous material on the membrane area, (2) increase the risk of sludge accumulation into the fibers; (3) damage the membranes. In addition, trash in the mixed liquor can plug the coarse bubble aerators used to scour the membranes which have holes ranging in size 5÷10 mm (Cötè *et al.*, 2006). In this case study, finally a fine punched hole sieve with openings of 1.5 mm was installed and the real performances were investigated. Sieving tests were performed directly in site, on grab samples both of wastewater and activated sludge from the bioreactor (samples volume ~ 200 L). According to the experimental results, the punched hole sieve was able to remove 70÷85% of the influent trash with size larger than 2 mm. Consequently, operating sludge age of ~15 days, the trash accumulated into the activated sludge was in the range 70÷100 $mg_{drytrash}$ L^{-1}. This level of trash into the activated sludge may be considered acceptable if compared with the operating total mixed liquor suspended solids (MLSS) of 6÷8 g L^{-1}.

The nature of the feed and the organic loading rate can be major factors that influence the amount and/or the bio-production of foulants (Le-Clech *et al.*, 2006). In this case study the wastewater was almost domestic, with seasonal fluctuating characteristics according to the summer tourism. Furthermore, a short-term (20÷30 days) random discharges of municipal landfill leachate into the municipal sewers were observed. Therefore, the MBR had to cope with both seasonal fluctuations (table 1, columns 1-2) and severe peaks loadings (see st.dev. - table 1, column 3).

Table 1. Main characteristics of the feeding sewage

	Municipal WW High Loading	Municipal WW Low Loading	Very unsteady nature of the feed
COD (mg L-1)	657 (±16%)	604(±16%)	417(±31%)
Total N (mg L-1)	64(±11%)	47(±9%)	54(±40%)
Total P (mg L-1)	7.2(±10%)	5 (±21%)	4.7(±30%)
TSS (mg L-1)	264(±29%)	255(±19%)	193(±56%)

Considering the operating parameters of the activated sludge process, the sludge age and the biomass concentration was maintained as low as necessary to achieve near complete nitrification. This strategy, based on periodically performed respirometry tests, allowed to optimize the oxygen transfer to the biomass (Germain *et al.*; 2007). The resulting MLSS in the AC tank was in the range 6÷8 g L^{-1} (sludge age 14÷21 days) according to the required nitrification potentials.

Basically, the hydrodynamic environment in a submerged MBR can be changed manipulating four main parameters: (1) the permeate flux; (2) the filtration cycle, (3) the aeration for membrane scouring; (4) the flowrate of recycled activated sludge (RAS).

In this case, the first plant start-up lasted about 50 days and began with a net flux of 21.4 LMH, that was increased up to 26.0 LMH by 3 days-long steps of 2-1,3-1,3 LMH. The permeate was sucked according to cycles of permeation(600 sec)/relaxation(60 sec), while the aeration for membrane scouring was intermittent on(10 sec)/off(10 sec).

With further concern to the aeration of the system, a couple of two-velocities blowers (reserve excluded) was used for the membrane scouring, while the biological process relied on two further and automatically controlled blowers. Therefore, the UF system could operate with four different coarse bubble air flowrates, specifically equal to 0.06; 0.12; 0.19; 0.26 $Nm^3\ m^{-2}_{membrane}\ h^{-1}$. These values are lower if compared to the ones reported for same membrane material (0,25÷0,54 $Nm^3\ m^{-2}_{membrane}\ h^{-1}$ for ZeeWeed® 500c) and much lower than those for flat sheet membranes (0,6÷1,5 $Nm^3\ m^{-2}_{membrane}\ h^{-1}$). The total recycles of activated sludge in case of intermittently aerated bioreactors for carbon and nitrogen removal are typically lower than the conventional multi-zone configurations. In fact, in this case study the total recycle ratio was about 2 and did not show significant drawbacks on the membrane long-term permeability and/or its decline.
As for the membrane cleaning, besides the routinely cleaning described in the materials and methods, after 8 months operation the membrane underwent to a recovery cleaning, that consisted in an overnight soak in hypochlorite solution. Further, a short-term (15÷20 days) lack of chemical cleaning occurred in correspondence of an extra-ordinary maintenance of the equipment for the hypochlorite dosage.

3.2 Overview on membrane permeability and fouling phenomena

According to the parameters of table 2, the whole operation can be divided in four steady state periods and two start-up phases. Furthermore, besides the recovery cleaning, also two short term singular events occurred.

Table 2.Overview on one-year plant operation

	Days	Net flux	Permeability @ 20°C	SAD	F:M	$MLSS_{UF}$
		LMH	LMH/bar	m^3/m^2 h	gCOD/ gVSS d	g/L
1st Start-Up	51	21.4-23.4-24.7-26	170 to 227	0,12		6 to 11
Run1	20	26	227	0,12	0,27	11
Run2	50	26	234	0,12	0,32	8
Singular event A	18		*No chemical cleaning*			
Run3	99	26	243	0,19	0,25	8
Maintenance	45		*Extra-ordinary maintenance*			
2nd Start-Up	10	26	186 to 190	0,19		4 to 8
Singular event B	20÷30		*Irregular peaks inloading*			
Run4	37	26	155	0,19	0,25	8

Table 2 suggests the following comments: (1) giving a cleaning protocol of 1 maintenance cleaning in place per week, the increase of aeration for membrane scouring did not give significant gain of permeability that could justify the increased power requirements; (2) MLSS concentration had a minor effect on membrane permeability, in fact a decrease from 11 to 8 g L^{-1} involved a gain of only 7 LMH/bar; (3) within the range occurred, the long-term fluctuation of F:M ratio, which has been proposed as fundamental parameter influencing the soluble microbial products (SMP) content and characteristics (Le-Clech *et al.* 2006), did not show significant effects on membrane permeability. Therefore, the membranes did not suffer from the seasonal fluctuations of the influent loadings. On the contrary, as expected severe unsteady operation worsened membrane fouling. This was observed for the two main singular events: (1) the absence of maintenance cleaning (see table 2, singular event A); (2) irregular peaks inloading (see table 2, singular event B). This impact is well visible in figure 2 where the Trans Membrane Pressure (TMP) trends of these periods are plotted together with a routinely trend (i.e.: table 2; run 2).

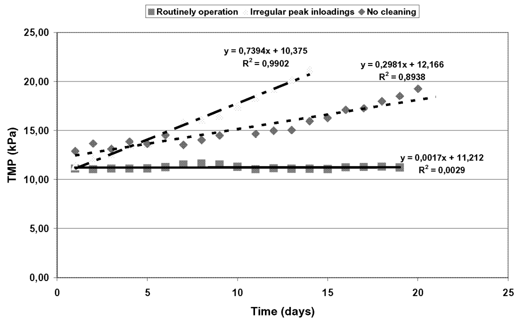

Figure 2. TMP trends in routinely and singular operation

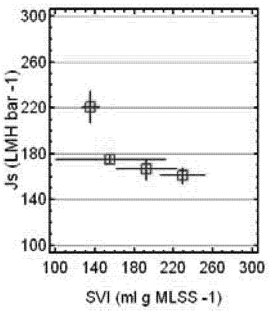

Figure 3. Permeability and SVI

Figure 2 shows that operating a stable net flux of 26 LMH and 1 maintenance cleaning per week can be considered a sustainable practice under routinely condition. As for the singular events, the case "A" caused a steady state TMP increase around 0,30 kPa day^{-1}. However, good permeability was re-established (see run 3, table 2) in about 20 days, using only hypochlorite maintenance cleaning. More severe fouling was observed for the singular event B. Here, the steady state TMP decline was about 0,74 kPa day^{-1}. The final loss of permeability seemed rather irreversible since it was not recovered by the routinely cleaning protocol. The resulting gap between run3 and run 4 might be due either to fouling/cake layer recalcitrant to the action of hypochlorite or to the changed characteristics of the activated sludge. To support this last hypothesis, the sludge volume index (SVI), which changed drastically within the singular event "B", has been analysed and is plotted versus the membrane permeability (Js) in figure 3. In this case the SVI should be taken as gross index of the state of the activated sludge and it can be correlated with the sludge filterability.

3.5 Power requirements and O&M costs

High power requirement is one of the key issues that limit the widespread application of MBRs for municipal wastewater treatment. In these systems the major part of the power is used in the aeration for both biological process and membrane scouring (figure 4).

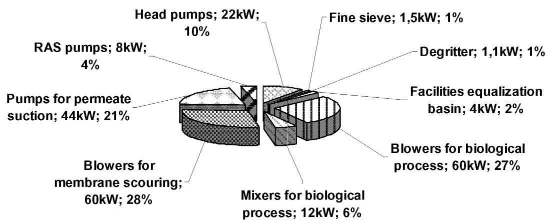

Figure 4. Power installed over the whole AC-MBR

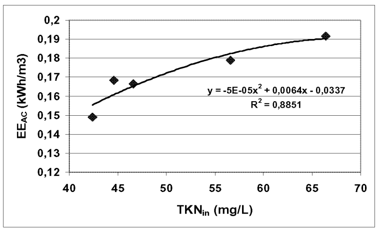

Figure 5. Energy consumptions for the biological process

Therefore, the AC-MBR design and operation was greatly focused on controlling and optimizing the aeration: (a) lower air was used for membrane scouring; (b) the AC process was able to optimize the biological denitrification and, consequently, the exploitation of nitrates-bound oxygen; (c) operating the bioreactor according to MLSS as low as required for the biological nitrogen removal allowed to optimize the oxygen transfer to the biomass (α factor).

As far as concern the energy consumptions of the biological process, the AC process makes use of energy depending on the durations of the aerobic and anoxic phases, which change according to the influent nitrogen content (figure 5). As far as the UF section, a meter of electrical input installed into the main switchboard pointed out specific power requirements of 0.16÷0.25 kWh m^{-3}, variable depending mainly on the aeration for membrane scouring. As a result, the power requirements for the whole treatment were in the range 0.44÷0.57 kWh m^{-3}.

As for the O&M costs of a large full scale MBR reported a specific cost of 0,26 €/unit permeate (Engelhardt and Linder, 2006), inclusive of the personnel and membrane replacement. In this case study, the real costs relating to the chemicals used to clean the membranes and the power consumptions have been determined. Considering the specific costs of 0.12 € kWh^{-1} for the power and 0.52 € kg^{-1} for the hypochlorite, the specific cost for power and chemicals were in the range 0,06÷0,08 € $m^{-3}_{permeate}$.

4. Conclusions

The paper gives an overview on the operation of an intermittent MBR for municipal wastewater treatment and reuse. As general remark, the privilege of coupling aeration control automation and membrane technology was demonstrated. In particular, the main conclusions are:

- the O&M routinely procedure was able to maintain a long-term permeability in the range 230÷240 LMH bar^{-1}. Major problems took place under severe unsteady state operation of the plant caused by random peaks in-loadings. On the contrary, the plant was able to cope with the long-term seasonal fluctuations of the in-loadings. Both the increase of specific aeration for membrane scouring from 0,12 to 0,19 Nm^3 h^{-1} $m^{-2}_{membrane}$, and the increase of MLSS for 8 to 11 g L^{-1} played a minor role under routinely maintenance chemical cleaning performed once a week;
- the appropriate management of the aeration was fundamental to achieve specific power requirements for the whole treatment in the range 0,44÷0,57 kWh/unit permeate also treating medium-high strength municipal wastewater. The O&M costs about power consumptions and chemical purchase were in the range 0.06÷0.08 €/unit permeate.

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