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A new and appropriate fibre sheet configuration for MBR technologies

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ABSTRACT

This paper deals with an innovative flat sheet membrane configuration developed by inge AG consisting of multitubular sheets arranged in parallel which can be easily backwashed. This new membrane combines the advantages of hollow fibres (backwashable) and flat sheet membranes (better control of the fluid distribution and module stackable) and should permit energy savings by reducing membrane aeration. Four vertically stacked modules were tested at pilot-scale at Anjou Recherche under typical biological operating conditions (MLSS = 11 g/L; SRT = 26 days). The first results are promising with regards to membrane performances though membrane irregularities led to some sludge deposit in some areas: modules were operated at a net flux up to 25 L h^{-1} m^{-2} with a SADm of 0.36 Nm^3 h^{-1} m^{-2} when backwash was done. However, some sheet damages occurred during the trials. Further membrane and module developments were therefore performed to limit membrane irregularities and achieve better membrane strength.

Keywords: Membrane bioreactor; Membrane configuration; Fibre sheet membrane

1. Introduction

The membrane bioreactor (MBR) process has been deemed to be a promising technology for wastewater treatment and water reuse. MBR systems have many advantages over conventional processes with their highly improved effluent quality as well as increased organic loading, reduced footprint and minimised mixed liquor production [1,2]. The first generation of MBRs were operated with organic or inorganic tubular membranes placed in external recirculation loops. Immersed bioreactors have been developed in the middle of the 1980s based on an idea of Yamamoto et al. [3] 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 [4]. In 2005, about 300 references of industrial applications (>20 m^3/d) and about 100 municipal wastewater treatment plants (>500 population equivalent) using this technology were listed in Europe [5]. Immersed MBRs with hollow fibres or flat sheet membranes are used in the majority of cases. MBR systems are expected to continue increasing in capacity and

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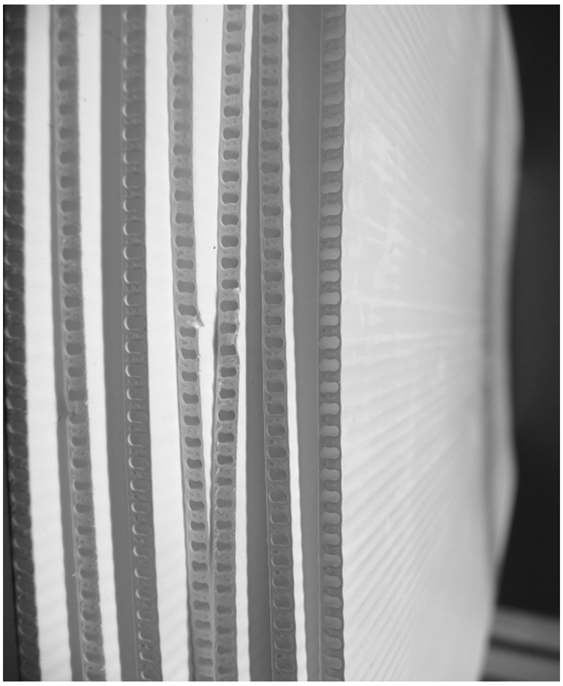

Fig. 1. inge multitubular sheets.

broaden their application area due to the increasingly stringent regulations [6] and the need for water reuse. However, membrane fouling remains the most serious problem affecting system performance. Fouling leads to a decline in permeate flux, requiring more frequent membrane cleaning leading to more frequent membrane replacement and resulting in increased operating costs. Actual academic and commercial research focuses on ways to improve the membrane equipment and operation in order to achieve a satisfying control of the fouling and energy savings, in particular, by decreasing the aeration demand. First, an adequate design of the filtration system is required to avoid sludge accumulation at the membrane's surface [7]. Moreover, stacking of flat sheet modules [8,9] and a homogeneous air distribution into the module [10] allows the reduction of air demand by using air bubbles to clean the most membrane surface as possible. An appropriate combination of filtration parameters like flux, relaxation [11], backwash time and frequency [12] would then enable the reduction of 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 8 to 25 Nm^3 air/m^3 permeate [2,9,13,14].

This paper deals with an innovative membrane configuration developed by inge AG within the framework of the AMEDEUS Project. The module resembles a flat sheet membrane system; nevertheless, each sheet is in fact formed by a range of horizontal tubes as shown in Fig. 1. The inge Fibre Sheet (FiSh®) technology therefore combines the advantages of:

- flat sheet systems in terms of (i) easy control of fluid distribution through the flat sheet network and (ii) having the possibility of stacking modules;
- hollow fibres systems in terms of (i) fouling control during operation (the membrane can be backwashed), (ii) mobility of the multitubular sheets in comparison with the usual flat sheet membranes in presence of aeration and (iii) membrane packing density.

The use of such a membrane should enable a reduction in coarse aeration needs, which significantly lower the operating costs of an MBR plant. The first pilot-scale trials using this new technology performed at Anjou Recherche are presented in this paper. Different operating conditions were tested during short-term and longer experiments in order to identify adapted operating conditions to this new technology.

2. Material and methods

2.1. inge filtration system

A process to manufacture a new membrane called FiSh® (Fibre Sheet) was recently developed by inge AG. It consists of a multitubular sheet as shown in Fig. 1. The inge sheets are manufactured in a single extrusion step, eliminating the need for gluing, and are only supported by the module housing. The resulting sheets are thinner than the conventional flat sheet membranes and allow the use of backwashes. Filtration occurs from the outside towards the inside of the sheets as for usual flat sheet membranes and permeate water is collected into the multitubes disposed horizontally.

Table 1
Membrane characteristics

Membrane material	PES (with additives for hydrophilicity and strength)
Mean pore size (μm)	0.2
Initial permeability (L h^{-1} m^{-2} bar^{-1})	2500
Membrane surface (m^2)	2.8 (× 4)

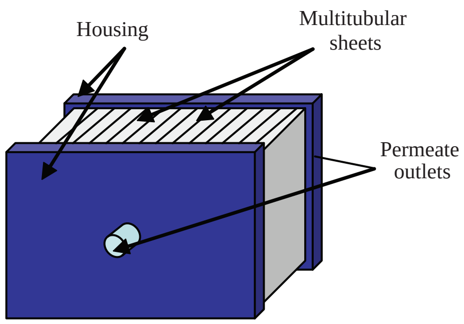

Fig. 2. inge module.

The characteristics of the membrane tested at Anjou Recherche are given in Table 1.

Each module is made up of 25 parallel sheets evenly distributed. The membrane sheets are fixed by moulded sides, in which the filtrate is collected (Fig. 2). To ensure maximum filtration and cleaning efficiency, an aeration system is installed below the filtration module stack. The resulting turbulence in the gas–liquid mixture ascending through the spaces between the individual membrane sheets enables the filtration cake deposits to detach. Relaxation and backwashing can be used to prevent clogging.

2.2. MBR pilot-plant

The performances of the modules were evaluated for 5 months in a MBR pilot-plant shown in Fig. 3 from May 2008 to September 2008 at Anjou Recherche (the Water Research Centre of Veolia). The pilot was fed with screened (1 mm drum screen) municipal wastewater from Maisons Laffitte (France) (Table 2).

The pilot was composed of a biological tank, a membrane tank and a permeate tank as shown in Fig. 3. The biological tank was 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 four vertically stacked modules of 2.8 m^2 were immersed. A pump was used to extract the permeate water from the membrane and the permeate water was collected in a storage tank. The concentrated mixed

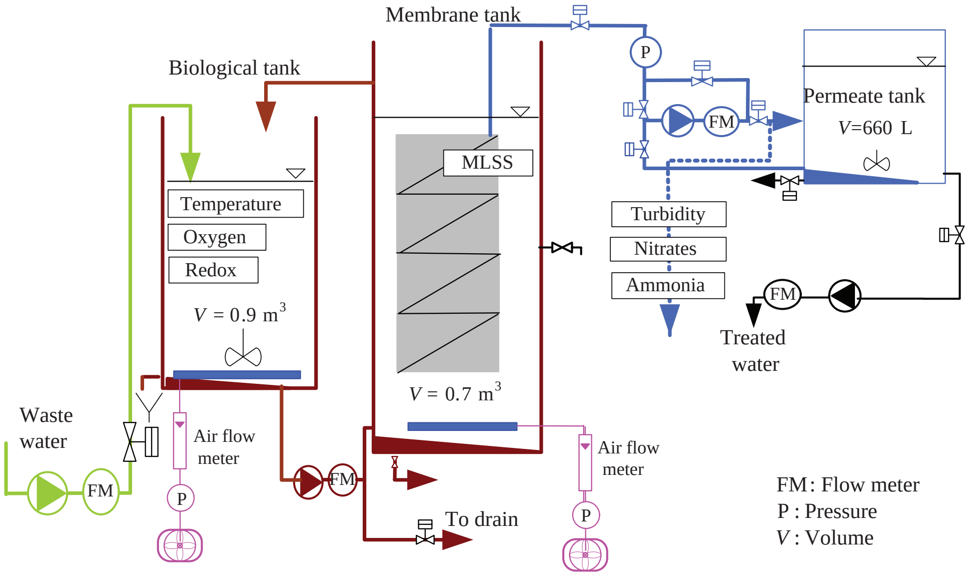

Fig. 3. Pilot-plant configuration.

Table 2
Wastewater characteristics

Parameter	Average	Minimum	Maximum	Sample number
TSS (mg/L)	220 ± 90	120	480	23
COD (mg/L)	470 ± 90	274	705	29
TN (mg/L)	54 ± 16	21	103	21
$N-NH_4^+$ (mg/L)	38 ± 7.6	23	54	26

Table 3
Biological operating conditions

Parameter	Design	Average	Minimum	Maximum
SRT (days)	25	26 ± 0.5	25	28
Volumetric loading rate (kg COD/m^3/day)	1.3	1.21 ± 0.32	0.68	1.99
F/M ratio (kg COD/kg MLSS/day)	0.13	0.11 ± 0.03	0.06	0.16
MLSS in the biological tank (g/L)	10	11 ± 1.3	8	13
HRT (h)	8	9.6 ± 1.5	7.3	12.9

liquor overflowed to the biological tank. The biological operating conditions, typical of MBR systems (Table 3), were maintained constant during all the trials in order to consider only the influence of the hydraulic operating conditions on the fouling behaviour of the membrane.

The hydraulic membrane performances (transmembrane pressure, filtration flow rate, temperature), the quality of the permeate water (ammonia and nitrate concentrations) and the characteristics of the sludge (suspended solids, redox, oxygen concentration) were monitored with a data acquisition system.

The permeability (Eq. (1)) and the resistance (Eq. (2)) were calculated using the following Darcy's law:

$$\mathrm{Lp}(20°\mathrm{C}) = \frac{Q_{\mathrm{filt}}}{S\Delta P}\frac{\mu(T)}{\mu(20°\mathrm{C})} \text{ with } \frac{\mu(T)}{\mu(20°\mathrm{C})} = e^{\left(-0.0239\cdot(T-20)/1.002\right)} \quad (1)$$

$$R = \frac{1}{\mu(20°\mathrm{C})\mathrm{Lp}(20°\mathrm{C})} \quad (2)$$

T: Temperature (°C)
R: Resistance (L^{-1})
Q_{filt}: Filtration flow rate ($\mathrm{L}^3\ \mathrm{T}^{-1}$)
Lp (20°C): Permeability at 20°C ($\mathrm{L}^2\ \mathrm{T}^{-1}\ \mathrm{M}^{-1}$)
S: Membrane surface (L^2)
$\mu(T)$: Viscosity at a temperature of T ($\mathrm{M\ L}^{-1}\ \mathrm{T}^{-1}$)
ΔP: Transmembrane pressure ($\mathrm{M\ L}^{-1}\ \mathrm{T}^{-2}$)
μ(20°C): Viscosity at 20°C ($\mathrm{M\ L}^{-1}\ \mathrm{T}^{-1}$)

The permeability and the flux are always reported at 20°C in this paper.

The fouling rate dR/dt corresponds to the increase of the resistance per hour. The specific air demand per permeate volume unit (SADp) and per membrane area (SADm) were also estimated for each operating condition.

Wastewater and permeate water analyses (TSS, COD, TN, $\mathrm{N-NH_4^+}$, pH, etc.) were performed daily to evaluate the treatment performances of the pilot unit, while the mixed liquor characteristics (MLSS, COD in the supernatant, CST, viscosity for a shear gradient of 1200s^{-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.

3. Results and discussion

3.1. Results at pilot-scale

The initial clean water membrane permeability of the four modules was about 2200 L h^{-1} m^{-2} bar^{-1}. The mixed liquor characteristics were typical of a MBR treatment (Table 4) throughout the course of the experiments.

During all the trials, the biological treatment followed the expectations in MBR: the COD concentration in the effluent was on average 14 mg/L, corresponding

Table 4
Mixed liquor characteristics in the biological tank

Parameter	Average	Minimum	Maximum	Sample number
MLSS (g/L)	11 ± 1.3	8	13	37
COD of the supernatant (mg/L)	33 ± 13	18	68	37
D50 (μm)	29.6 ± 1.8	27.2	32.3	7
Viscosity for a shear gradient of 1200 s^{-1} (Pa s)	0.008 ± 0.001	0.007	0.010	6
CST (s)	11 ± 3	8.1	16.1	5
Polysaccharides in supernatant (mg/L)	2.7 ± 0.9	2	4	7
Proteins in supernatant (mg/L)	13.5 ± 3.5	8.0	18.9	7

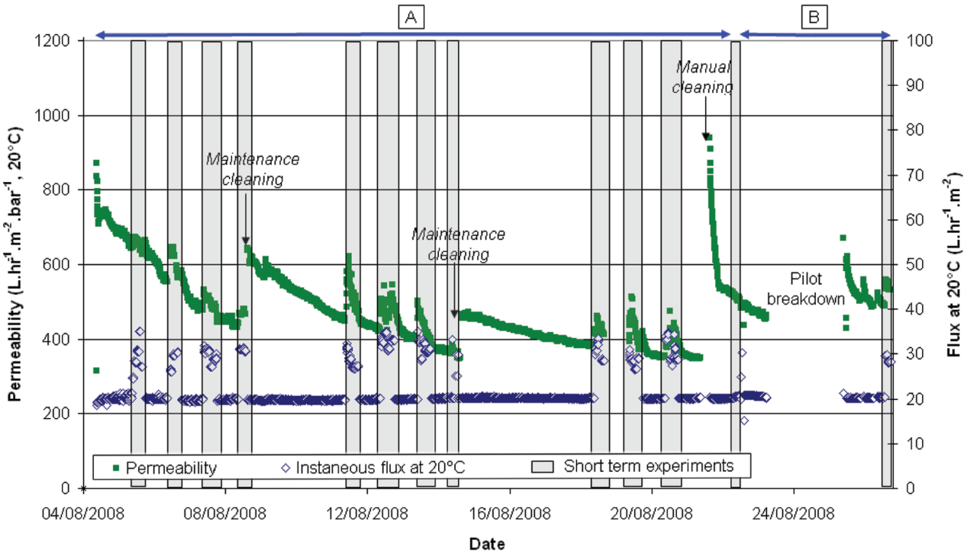

Fig. 4. Membrane performance evolution. (A) Filtration of 6 min at 20 L h^{-1} m^{-2}/relaxation of 1 min – SADm = 0.27 Nm^3 h^{-1} m^{-2}. (B) Filtration of 6 min at 20 L h^{-1} m^{-2}/relaxation of 1 min – SADm = 0.36 Nm^3 h^{-1} m^{-2}.

to a removal efficiency of 96.5%. The average total nitrogen removal efficiency was 73% over the course of the experiments but membrane air flow rate changes led to some variations (12%) of this parameter.

The first experiments at pilot-scale showed that the inge FiSh® modules can operate at a permeability between 400 and 600 L h^{-1} m^{-2} bar^{-1} for a net flux of 17 L h^{-1} m^{-2} when operating as follows: 6 min of filtration followed by 1 min of relaxation along with a continuous membrane air flow rate of 0.27 Nm^3 h^{-1} m^{-2} during the first three weeks (SADp = 16 Nm^3 air/m^3 permeate) and 0.36 Nm^3 h^{-1} m^{-2} during the last week (SADp = 21 Nm^3 air/m^3 permeate). Fouling rates ranging from 0.002 × 10^{12} to 0.004 × 10^{12} m^{-1} h^{-1} were noticed under those operating conditions. Increasing membrane aeration did not improve the filtration performance (Part 2 of Fig. 4). On the contrary, maintenance cleanings performed weekly helped to maintain good permeability.

To identify the most adapted filtration operating conditions for this new membrane technology, short-term experiments were performed (gray parts of Fig. 4) by varying the filtration time, the relaxation time, the backwash time, the backwash flux and the membrane aeration flow rate. The net flux was fixed at 25 L h^{-1} m^{-2} to achieve significant fouling rate differences between experiments. The aeration flow rates were chosen in order to have SADm values less than 0.6 Nm^3 h^{-1} m^{-2} and SADp values less than 25 Nm^3 air/m^3 permeate which are in accordance with the values given for current membrane systems (SADm = 0.2–0.8 Nm^3 h^{-1} m^{-2} and SADp = 8–25 Nm^3 air/m^3 permeate) [2,9,13,14]. Experiments were performed during 1 h and were followed by 30 min of relaxation with an air flow rate of 0.45 Nm^3 h^{-1} m^{-2}. This test duration was chosen in order to perform the experiments during a few weeks in order to keep similar mixed liquor characteristics during all short-term experiments.

Six short-term experiments given in Table 5 showed a resistance increase inferior to 0.01 × 10^{12} m^{-1} h^{-1} indicating good fouling control. To verify the efficiency of these operating conditions, longer experiments lasting 1–2 days were performed. The operating conditions of these tests and the obtained resistance increase during short and corresponding long-term experiments are given in Table 5.

The short-term experiments were not totally representative of the longer experiments. The resistance increase in 1 day was not exactly the same as the resistance increase observed in 1 h (Table 5) because small variations can occur through the day as shown in Fig. 5 and a stabilisation time can be required. Some negative fouling rates were also obtained during the short-term experiments in particular after previous experiments leading to strong fouling.

For the longer experiments, the resistance increase remained low (under 0.01 × 10^{12} m^{-1} h^{-1}) as shown in Fig. 5 when operating with a net flux of 25 L h^{-1} m^{-2}.

The first experiment led to a fouling rate of 0.008 × 10^{12} m^{-1} h^{-1} over 1 day, but results could have been influenced by a previous pilot breakdown. Therefore, this experiment was repeated on September 9th and after a day, the fouling rate was only 0.003 × 10^{12}

Table 5
Experiment conditions which gave satisfying results during short-term and corresponding longer experiments (net flux of 25 L h^{-1} m^{-2})

Experiment number	Filtration time (s)	Relaxation/ backwash time (s)	Backwash flux (L h^{-1} m^{-2})	SADm (Nm^3 h^{-1} m^{-2})	Instantaneous flux (L h^{-1} m^{-2})	SADp (Nm^3 air/m^3 permeate)	Short-term experiments dR/dt (10^{12} m^{-1} h^{-1})	Longer experiments dR/dt (10^{12} m^{-1} h^{-1})
1	156	82	0[a]	0.36	38	14	−0.016	0.003–0.008
2	360	82	0[a]	0.51	31	20	−0.004	0.003
3	240	120	0[a]	0.45	38	18	0.009	0.002
4	480	120	0[a]	0.27	31	11	0.003	0.003
5	360	22	130[b]	0.36	34.5	14	0.0095	0
6	480	14	100[b]	0.45	28.6	18	−0.035	Not performed

[a] With relaxation.
[b] With backwash.

m^{-1} h^{-1}. Experiments 2, 3 and 4 showed relatively similar fouling rates of 0.002–0.003 × 10^{12} m^{-1} h^{-1} which is comparable to the fouling rate obtained with a lower net flux of 17 L h^{-1} m^{-2}. Experiment 4 showed the lowest SADm (0.27 Nm^3 h^{-1} m^{-2}) and therefore showed the most suitable operating conditions when using relaxation.

The implementation of backwash for experiment 5 finally led to a stable permeability with a resistance increase close to 0 m^{-1} h^{-1} for a net flux of 25 L h^{-1} m^{-2} and a SADm of 0.36 Nm^3 h^{-1} m^{-2}. These last operating conditions similar to those for current membrane systems therefore seemed promising. However, membrane breakage occurred after several hours of operation under these conditions and the tests were stopped. Membrane system robustness therefore seemed to be suboptimal.

During the trials, visual observations of the membrane also showed that irregularities present at the membrane surface led to sludge accumulation in some areas (Fig. 6). Without these irregularities, better membrane performances with a better use of the membrane surface could be achieved. Design and aeration system improvements should enable better membrane performances and stacking of more modules could also enable the decrease of the aeration even more [8,9]. Further membrane and module developments are

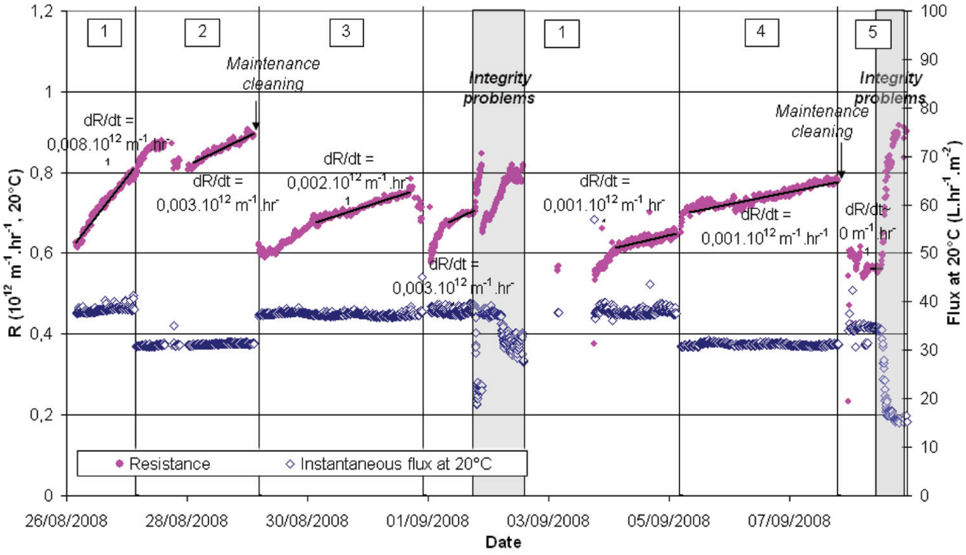

Fig. 5. Resistance and flux evolution for selected operating conditions.

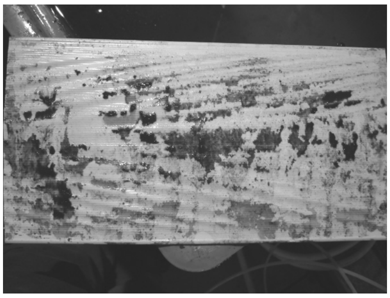

Fig. 6. Membrane surface after operation.

therefore required before being able to optimise the filtration parameters any further.

3.2. inge membrane development

The inge membrane is a totally new concept and further research has been performed to improve the module design.

The research was first focused on the membrane manufacturing. During the manufacturing of the FiSh® membranes, many parameters need to be controlled in order to obtain the desired permeability, pore size and pore size distribution, hydrophilicity, strength and flexibility. For the first membranes tested at Anjou Recherche, inge achieved a good pore size control on the outside surface of the membrane (in terms of overall porosity and absolute pore size) and the membrane had a relatively good strength. However, the first modules to be tested presented some unwanted irregularities which had some consequences on fouling behaviour and cleaning effectiveness: during coarse aeration, air bubbles could choose a preferential path and fail to clean some areas of the membrane sheets as shown in Fig. 6. Further developments of the membrane material were therefore performed to limit these irregularities.

The trials at pilot-scale highlighted in addition that some sheet breakage can occur during operation with mixed liquor. Indeed, contrary to flat sheet membranes, the FiSh membrane has some flexibility and can slightly move in the presence of aeration and during backwash. This movement can improve the ability to clean the membranes; however it is also a possible reason for the observed damages of the membrane. In order to minimise the risk of sheet breakage in the next module generation, this movement was investigated.

Following these investigations, new improved and more resistant modules having fewer irregularities were built and are currently being tested.

4. Conclusion

A new flat sheet membrane module consisting of multitubular sheets arranged in parallel which are thinner than conventional flat sheet membranes and backwashable was developed by inge. First modules were tested at Anjou Recherche to verify the advantages of such membrane configuration in terms of membrane performances when using backwash. Promising results with regards to the membrane performances were obtained even though some irregularities at the membrane surface led to some sludge deposits. The membrane permeability stabilised for a net flux of 25 L h^{-1} m^{-2} and a SADm of 0.36 Nm^3 h^{-1} m^{-2} when using backwash. However, further membrane and module developments are required to improve the membrane robustness and filtration system design to further optimise the filtration parameters. Several innovations were already performed by inge to limit the membrane irregularities and achieve a better strength of the membranes. New modules incorporating these changes are currently being tested at Anjou Recherche.

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References

[1] A. Tazi-Pain, J.-C. Schrotter, N. David and H. Buisson, First year of operation of the first full scale sequenced aeration MBR for municipal wastewater treatment in Perthes-en Gâtinais, Proceedings of Engineering with Membranes, vol. 1, 2001, pp. 43-48.

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

[3] K. Yamamoto, M. Hiasa, T. Mahmood and T. Masuo, Direct solid–liquid separation using hollow fiber membrane in an activated-sludge aeration tank, Water Sci. Technol., 21 (1989) 43-54.

[4] P. Côté, H. Buisson and M. Praderie, Immersed membranes activated sludge process applied to the treatment of municipal wastewater, Water Sci. Technol., 38(4-5) (1998) 437-442.

[5] B. Lesjean and E.H. Huisjes, Survey of European MBR market: trends and perspectives, Desalination, 231(1-3) (2008) 71-81.

[6] J. Peeters, J. Pawloski and J. Noble, The evolution of immersed hollow fibre membrane aeration for MBR, IWA 4th International Membrane Technologies Conference, Harrogate, UK, 2007.

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

[8] S. Judd, Fouling control in submerged membrane bioreactors, Water Sci. Technol., 51(6-7) (2005) 27-34.

[9] A. Grélot, A. Tazi-Pain, L. Weinrich, B. Lesjean and A. Grasmick, Evaluation of a novel flat sheet MBR filtration system, Desalination, 236 (2009) 111-119.

[10] E. Nguyen Cong Duc, L. Fournier, C. Levecq, B. Lesjean, P. Grelier and A. Tazi-Pain, Local hydrodynamic investigation of the aeration in a submerged hollow fibre membranes cassette, J. Membr. Sci., 321 (2008) 264-271.

[11] S.P. Hong, T.H. Bae, T.M. Tak, S. Hong and A. Randall, Fouling control in activated sludge submerged hollow fiber membrane bioreactors, Desalination, 143 (2002) 219-228.

[12] P. Schoeberl, M. Brik, M. Bertoni, R. Braun and W. Fuchs, Optimization of operational parameters for a submerged membrane bioreactor treating dyehouse wastewater, Separat. Purif. Technol., 44 (2005) 61-68.

[13] S. Judd, Membrane bioreactors: state of the art, Proc. AWA Membranes Specialty Conference II, Melbourne, 2007.

[14] A. Garcès, W. De Wilde, C. Thoeye and G. De Gueldre, Operational cost optimisation of MBR Schilde, IWA 4th International Membrane Technologies Conference, Harrogate, UK, 2007.