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Influence of intermittent aeration and relaxation on a side-stream membrane bioreactor for municipal wastewater treatment

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ABSTRACT

This paper is focusing on filtration of municipal wastewater with intermittent aeration and relaxation periods for a side-stream MBR in which filtration is performed with outside/in hollow-fibre membranes. In this semi-industrial scale side-stream MBR, hollow fibres are put in an external cartridge where sludge at low velocity and air are circulating around and inside the fibre bundle (in a confined system). Short-term experiments were performed under high fouling conditions but low energy consumption in order to determine and to characterise the influence on fouling of intermittent aeration and permeation. Discontinuous aeration is divided in two periods with two different air flow rates, a high one during a short duration and a lower one during a longer period. Relaxation was also studied by alternating on and off permeation periods. After that, aeration and permeation sequences were coupled. Results showed that for the same global air flow rate injected and for the same filtered volume, a punctually high aeration flow rate combined with a low aeration flow rate for the rest of time is better than a continuous one. Furthermore, filtration cake is removed more easily at the end of the experiment if aeration is discontinuous. Nevertheless, the aeration rate should be sufficient (above 0.112 $Nm^3\,h^{-1}$ corresponding to specific aeration demand per membrane square meter (SAD_m) of 0.074 $Nm^3\,h^{-1}\,m^{-2}$ and specific aeration demand per permeate cubic meter (SAD_p) of 0.373 $Nm^3\,m^{-3}{}_p$) to prevent fouling. Lower fouling was obtained by discontinuous permeation in comparison to continuous permeation. Moreover specific aeration energies are only slightly higher for discontinuous permeation but the cake density is significantly lower and the deposit can be more easily removed by backwash. This study confirms the interest of operation with relaxation periods.

Keywords: Activated sludge; Fouling; Gas flow rate; Hollow fibre membranes; MBR Relaxation

1. Introduction

Membrane bioreactors (MBR) are a promising way for wastewater treatment and their development is growing exponentially. Among the different configurations, the side-stream MBR (external configuration) enables interesting membrane performances [1]. In the side-stream configuration (Fig. 1), the filtration module is outside the bioreactor and the feed is sent to the module bottom using a very low liquid velocity. The concentrate is recycled in the bioreactor at a low velocity. In addition,

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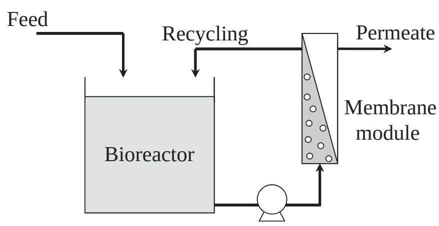

Fig. 1. Scheme of the side-stream configuration.

aeration is provided below the fibres in order to prevent fouling (Fig. 1).

The common parameters used by membrane suppliers to quantify aeration are the membrane and permeate specific aeration demands (SAD_m and SAD_p), calculated by the air flow rate divided by the membrane area and the permeate flow rate respectively. Examples of commonly used SAD are reported in a deliverable of the EUROMBRA project [2]: SAD_m values recommended by membrane suppliers are 0.15, 0.20, 0.33 and 0.98 $Nm^3\ h^{-1}\ m^{-2}$ corresponding to 15, 19, 27 and 79 $Nm^3\ m^{-3}{}_p$ SAD_p values respectively for Polymem, Memcor, Zenon (hollow-fibres) and Kubota (flat sheet) membranes.

Previous studies in our group focused on the injection of air in continuous mode during filtration with bentonite suspensions in a semi-industrial scale side-stream MBR [3]. It was found that higher air flow rates allow to lower and to prevent particle fouling. However, these results in continuous aeration mode have to be confirmed for real biological feed as an activated sludge.

More recently, a discontinuous aeration mode has been studied. In a survey realised in the frame of the AMEDEUS project [4], four of nine questioned suppliers are using discontinuous aeration. Indeed, this intermittent aeration showed a benefit to decrease fouling [5] and influenced biological parameters by increasing biological oxygen demand and nitrogen removal [6]. It was found also that microbial activity was a little bit more effective according to the aeration on/off time [6]. Discontinuous aeration is also used to decrease the energy cost induced by aeration. The possibility to decrease fouling and SAD in the same time is an advantage for MBR applications. However, some authors found that membrane filtration performance was not affected by either applying a 10 s on/30 s off intermittent aeration control or by reducing the airflow rate by 50% [7] so the interest of sequential aeration is still questionable.

It is also possible to influence membrane fouling by alternating on and off permeation periods. These relaxation periods might have marked effects on filtration behaviour [8–11]. Howell et al. [10] and Wu et al.

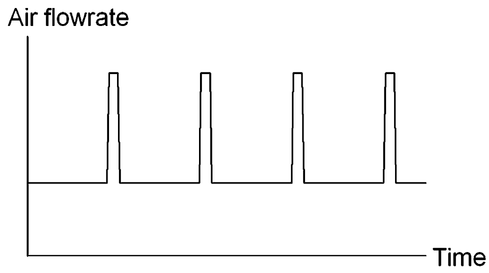

Fig. 2. Discontinuous aeration scheme.

[11] performed a cyclic operation with 480 s filtration and 120 s stoppage, so with 20% of the time without filtration. Three companies, Zenon, Kubota and Memcor, announced an optimum of 540/60 s on/off filtration periods which correspond to 10% of the time without permeation. Intermittent permeation may be considered as a membrane cleaning technique where permeation is suspended periodically. The driving force is then stopped during these periods and particles are not more held to the membrane. The cake deposit structure may be modified during the relaxation period and then this cake may be more easily removable by liquid or air flows. Particles deposited on the membrane may be more easily removed by the liquid flow during the suspension of permeation. A novel filtration mode has also been developed by Wu et al. [12] which consists to put a high instantaneous flux initially for a short time (120 s) followed by a longer filtration (290 s) at lower flux. This strategy reduces both the cake and gel layers.

The originality of this work is to combine these two techniques (relaxation periods and aeration intermittence) during filtration of activated sludge. In our study, discontinuous aeration is operated in a specific and original way: aeration is never stopped but its intensity is changed and high air flow rate are periodically used during short periods, as described on Fig. 2.

The objective is here to check if it is possible to modify the deposit with the short-time high aeration rate. The aims of this paper are to study the influence of discontinuous aeration and permeation on fouling properties. Experiments were performed with a semi-industrial scale pilot plant operated with MBR sludges sampled in a similar side-stream MBR plant. The influence of the following aeration and filtration sequences was studied:

- Continuous aeration and permeation operated at constant flow and used as reference experiments,
- Discontinuous aeration with high air flow rate during a short time while continuous filtration,
- Discontinuous permeation with relaxation periods (permeation off) while continuous aeration,

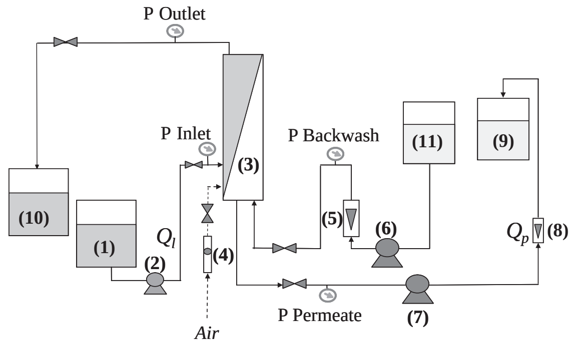

Fig. 3. Pilot plant scheme.

- Combinations of coupled discontinuous aeration and permeation.

The influence of these aeration and permeation sequences on sludge biological properties was also studied in the same time and is presented in another paper [13].

2. Materials and methods

2.1. Pilot plant

A schematic diagram of the MBR pilot plant is shown in Fig. 3. Filtration was operated in outside/in mode with hollow fibre membranes arranged in a 1 m height and 0.068 m diameter (D_c) cylindrical cartridge (3) which was external to the bioreactor. A maximum of 100 L of MBR activated sludge were fed in a stirred tank (1), with oxygen and temperature regulations and pH control. Real sewage was fed from this tank to the module inlet with a peristaltic pump (2) and the liquid flow rate Q_l was regulated by varying the rotation frequency of this pump. The feed solution was circulated externally to the fibres at a low liquid velocity (0.009 m s^{-1}). The concentrate was not recycled to the feed tank and was collected in an external storage tank (10). Permeate flow rate ($Q_p = 0.5 \times Q_l$) was measured with an electromagnetic flow meter (8)

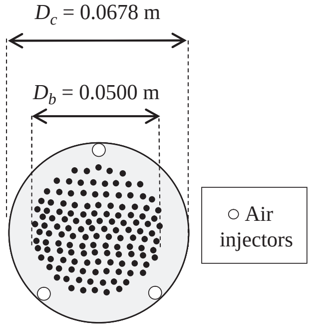

Fig. 4. Bundle base of the membrane module.

and controlled by a suction pump (7). Permeate was also collected in a storage tank (9). Ultrafiltered water (11) was used at the beginning and the end of every experiment for a backwash sequence regulated with a pump (6) and a flowmeter (5). Air (dotted lines in Fig. 3) can be injected at the bottom of the module through three porous bubble diffusers of 5 mm diameter placed around the bottom of fibre bundle (Fig. 4). Air flow-rate was regulated using a rotameter (4). Pressures were measured every 30 s at the inlet (P_i), outlet (P_o) and permeate (P_p) sides of the module in order to calculate the transmembrane pressure $\left(TMP = \frac{P_i+P_o}{2} - P_p\right)$. TMP time-variation can thus be measured during the experiment. TMP was plotted vs. filtered volume.

2.2. Feed and storage tank

Experiments were carried out with an activated sludge (SRT of 40 days) sampled from a side-stream MBR pilot plant (so the same configuration as for the pilot studied here) in Labège (France). This effluent was put (1 h after sampling) in a stirred tank to avoid settling and the temperature was kept constant at 14 $\pm$ 0.1°C to have comparable experiments. The sludge was aerated (oxygen concentration of 2.5 $\pm$ 0.5 mgO_2/L) during 2.5 h before every experiment in order to provide aerobic conditions to the sludge. The pH was regulated between 6.8 and 7.2. All experiments were performed with a single passage of the feed inside the module in order to avoid mixing of concentrate and feed in the bioreactor.

In order to obtain comparable experiments, some successive experiments were performed with the same sludge samples. Two pairs of experiments are coupled together: the experiments I&II and III&IV (cf. Table 2). At the end of experiments I and III, permeate and concentrate were remixed together in order to perform a second experiment (experiments II and IV respectively) with the same sludge. MLSS and mean floc sizes of new and remixed sludges were compared and were identical. All other experiments (V, VI and VII) were realised with new sludge samples. The MLSS concentrations were compared between all experiments and were the same (7 $\pm$ 0.7 g L^{-1}). Average particle diameter was measured (Mastersizer Malvern 2000) assuming that particles are spherical and also compared for all experiments. An example is presented on Fig. 5.

Whatever the experiment, mean volume and number diameters were the same for all experiments (respectively 100 $\pm$ 30 and 2 $\pm$ 0.5 μm). It can be assumed that the influence of particles on fouling will be the same for all experiments.

Table 1
Specifications of the semi-industrial scale module

	Lp_o at 20°C	External fibre diameter	Mean pore size	$A_{membrane}$	Module PD $A_{fibres}/A_{cartridge}$	Bundle PD A_{fibres}/A_{bundle}
Module	(L h^{-1} m^2 bar^{-1})	(mm)	(μm)	(m^2)	(–)	(–)
1MS	450	1.45	0.08	1.51	0.20	0.66

2.3. Membrane module

The module consisted of a 0.068 m inner diameter cartridge containing one 0.05 m diameter (D_b) bundle of polyethersulfone hollow-fibres with a 0.08 μm as the mean pore size (ultrafiltration membranes) and an external fibre diameter of 1.45 mm. This module, with an active filtration area $A_{membrane}$ of 1.51 m^2, an initial permeability Lp_o of 450 $\pm$ 30 L h^{-1} m^2 bar^{-1} and a fibre packing density (PD) equal to 20%, was provided by the French company Polymem (Toulouse, France). The bottom ends of the fibres are potted in an epoxy resin base. The individual fibres are sealed at the top end and are free to move from side to side within the cartridge. Permeate is removed from the bottom of the module by suction through the fibres in outside/in filtration mode. The characteristics of the membrane module are presented in Table 1, with its module and bundle PDs, which are the fibre cross sectional A_{fibres} area divided respectively by the cartridge $A_{cartridge}$ and the bundle A_{bundle} cross sectional areas.

2.4. Filtration and aeration modes

Experiments were performed in short-term periods (less than 1 h) at same constant instantaneous permeation flux J_p (30 L h^{-1} m^{-2}) for different aeration rates and durations, relaxation periods, and combinations of these actions. This flux is the same for all experiments in order to keep the same driving force and bring the same quantity of compounds on the membrane for all the experiments. Permeate flux is then equal to 45.3 L h^{-1} and recycling liquid flowrate to 90.6 L h^{-1} (Q_l = 2 × Q_p) that implies a maximum filtered volume of permeate equal to 50 L (half of initial volume).

Two filtration modes were used. A continuous one which consists on pumping the permeate with the suction pump continuously during the whole experiment. The second one is a discontinuous mode: the pump was put successively on and off (on/off permeation periods: 300/60 and 450/60 s) thanks to an automatic temporizer. The off permeation period is considered as a relaxation period. At the end of each relaxation period, for the next filtration period, the permeate flow was regulated manually to correspond to the required instantaneous flux (30 L h^{-1} m^{-2}). The corresponding net flux J_{net} (L h^{-1} m^{-2}) was calculated taking into account the periods without filtration.

Continuous and discontinuous aeration modes were used. Continuous aeration consists on maintaining the air flow rate constant during the whole experiment. Discontinuous aeration consists in using successively low

Table 2
Experiment conditions in terms of aeration and sequencing periods

Experiment number	I	II	III	IV	V	VI	VII
Aeration							
Mode	c	c	c	d	c	c	d
On/off periods (s)				290/10			450/60
Q_g (Nm^3 h^{-1})	0.195	0.390	0.195	0.145/1.641	0.195	0.195	0.112/0.820
$Q_{g\ net}$ (Nm^3 h^{-1})	0.195	0.390	0.195	0.195	0.195	0.195	0.195
U_{gs} (m s^{-1})	0.019	0.038	0.019	0.014/0.158	0.019	0.019	0.011/0.079
SAD_m (Nm^3 h^{-1} m^{-2})	0.129	0.258	0.129	0.096/1.086	0.129	0.129	0.074/0.543
SAD_p (Nm^3 $m^{-3}{}_p$)	4.3	8.6	4.3	3.2/36.4	4.3	4.3	2.5/18.2
Filtration							
Mode	c	c	c	c	d	d	d
On/off periods (s)					300/60	450/60	450/60
J_p (L h^{-1} m^{-2})	30.0	30.0	30.0	30.0	30.0	30.0	30.0
$J_{p\ net}$ (L h^{-1} m^{-2})	30.0	30.0	30.0	30.0	25.0	26.5	26.5

c, continuous; d, discontinuous.

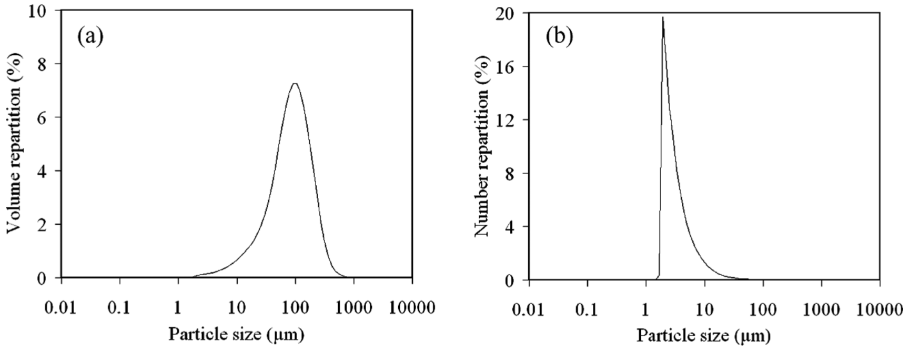

Fig. 5. Repartitions in (a) volume and (b) number of particle sizes in the activated sludge.

and high air flow rates by rotating the air flowmeter (low/high aeration periods: 290/10 s with flow rates Q_g = 0.145/1.62 Nm^3 h^{-1} which corresponds to U_{gs} = 0.014/0.158 m s^{-1} and SAD_m = 0.096/1.086 Nm^3 h^{-1} m^{-2}).

Aeration and relaxation were also combined together. A high aeration flow rate (Q_g = 0.82 Nm^3 h^{-1}, U_{gs} = 0.079 m s^{-1}, SAD_m = 0.543 Nm^3 h^{-1} m^{-2}) was used during each 60 s relaxation period and a low aeration flowrate (Q_g = 0.112 Nm^3 h^{-1}, U_{gs} = 0.011 m s^{-1}, SAD_m = 0.073 Nm^3 h^{-1} m^{-2}) was used during the 450 s filtration period. All the conditions of these experiments are presented in Table 2.

SAD of continuous aeration experiments are rather lower than those used commonly in submerged MBR processes [4,14–16].

2.5. Gas and liquid flow rates and velocities

Q_g (Nm^3 h^{-1}) is the gas flow-rate at standard temperature and pressure conditions (STP, at 0°C and 1 atm). Q_g was between 0.112 and 1.64 Nm^3 h^{-1}. Two specific aeration demands (SAD) were calculated with following equations. The conditions used here correspond to membrane specific aeration demand (SAD_m) between 0.074 and 1.093 Nm^3 h^{-1} m^{-2} and permeate specific aeration demand (SAD_p) between 2.45 and 36.2 Nm^3 $m^{-3}{}_{p}$. Moreover, it corresponds to gas superficial velocities U_{gs} between 0.011 and 0.158 m s^{-1}.

$$SAD_m = \frac{Q_g}{A_{membrane}}, SAD_p = \frac{Q_g}{Q_p}, U_{gs} = \frac{Q_g}{A_{free}}, U_{ls} = \frac{Q_1}{A_{free}},$$
$$A_{free} = A_{cartridge} - A_{fibres}$$

Q_l (Nm^3 h^{-1}) is the liquid flow-rate at STP and corresponds to a superficial liquid velocity U_{ls}. Q_l was fixed equal to $2Q_p$ so it corresponds to 90.6×10^{-3} Nm^3 h^{-1} and U_{ls} equal to 0.009 m s^{-1}.

2.6. Cleaning sequences and backwashes

After every experiment, a backwash was performed with ultrafiltered water at 1.5 bar in reverse filtration to remove particles. After this, cleaning was realised with a solution of sodium hydroxide ([NaOH] = 4 g L^{-1}) and chloride ([Cl_2] = 200 ppm) which was filtered from the inside to the outside of the hollow fibres during 30 min and then kept in contact without filtration during 1.5 h to clean the membrane. Thanks to this procedure, membrane permeability was the same at the beginning of each experiment (450 $\pm$ 30 L h^{-1} m^2 bar^{-1}) and the membrane supposed to be in the same chemical and physical states.

2.7. Fouling velocities

TMP was measured as a function of time and the corresponding fouling resistance (R) was calculated. The fouling velocity expressed in terms of the filtered volume derivative of the fouling resistance (dR / dV) was calculated by linear regression to obtain the slope of $R = f(V)$ during different periods. For experiments I to III, with continuous aeration and permeation, the duration of the period was 300 s which corresponds to a filtered volume of 3.76 L. For experiment IV with discontinuous aeration, the same period was chosen so the pressure recorded just at the end of the high air flow rate period was considered for the calculation of the fouling velocity. For experiment V with discontinuous filtration, the fouling velocity was calculated taking into account only the filtration period, so during 300 s. The experiments VI and VII have permeation periods of 450 s so the fouling velocity was calculated on this duration, which correspond to a filtered volume of 5.66 L.

Characteristic curves were thus obtained by the plot of TMP and fouling velocity as a function of the filtered volume in order to compare the different experiments.

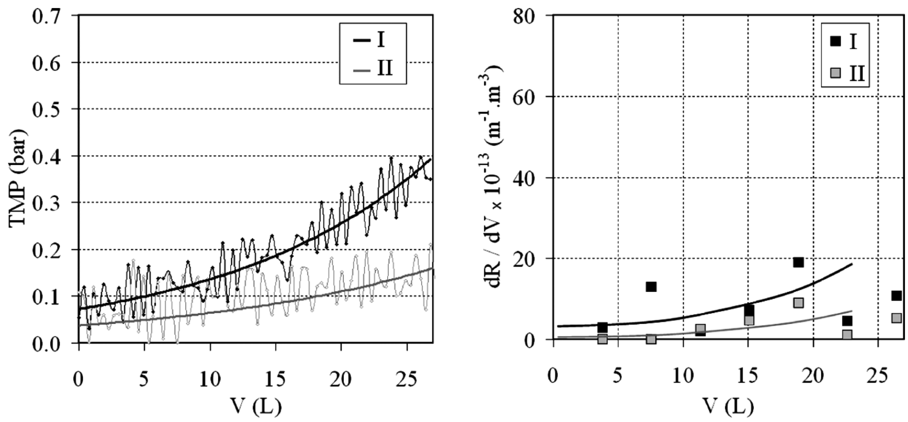

Fig. 6. Influence of air flow rate on fouling in continuous aeration mode. $J_p = 30$ L h^{-1} m^2, $U_{ls} = 0.009$ m s^{-1}, with (I) $U_{gs} = 0.019$ m s^{-1}/$SAD_m = 0.129$ Nm^3 h^{-1} m^{-2} (black) and (II) $U_{gs} = 0.038$ m s^{-1}/$SAD_m = 0.258$ Nm^3 h^{-1} m^{-2} (grey).

3. Results and discussions

3.1. Influence of gas flow rate on fouling

Two experiments (I&II) with two different aeration rates were performed in order to validate the influence of an increase of gas flow rate on fouling ability [3] with an activated sludge. All other parameters were identical (same sludge, $U_{ls} = 0.009$ m s^{-1}, $J_p = 30$ L h^{-1} m^{-2}). The superficial gas velocities tested were 0.018 and 0.038 m s^{-1} which correspond to SAD_m equal to 0.129 and 0.258 Nm^3 h^{-1} m^{-2}. The comparison of these two experiments is presented in Fig. 6.

The gas flowrate has no influence on fouling until $V = 10$ L (Fig. 6). Indeed, below this volume, TMP is rather low and fouling velocities are negligible. Above a 10 L filtered volume, fouling velocity is increasing for the lower gas flow rate whereas for the higher gas flow rate, fouling velocity remains low (the exception at $V =$ 11 L was not considered). It is clearly shown on Fig. 6 that the higher the aeration rate, the lower the fouling velocities. The same tendency was found in previous experiments with the same system with clay suspensions [3]. It confirms the interest of aeration for complex and real sewages. However, the decrease of fouling with an increase of air flow rate has a known limit: indeed some authors have demonstrated that increasing more and more aeration after reaching an optimal value can provoke negative aspects [17–20]. One of the solutions to prevent fouling in this side-stream process could be to use quite high aeration rates.

Nevertheless, using high aeration in continuous mode may be expensive because aeration contributes to a large part of economical dispenses in MBR plants [4]. In our experiments, the highest aeration rate corresponds to a specific energy consumption of 0.42 kWh m$^{-3}{}_{\text{p}}$, which remains in the range of values used by membrane companies (specific filtration energy consumption 0.2–0.8 kWh m$^{-3}{}_{\text{p}}$ [4]). However, in order to test the feasibility to operate at a lower energetic cost, the next experiments were performed at $SAD_m =$ 0.129 Nm^3 h^{-1} m^{-2} always with a high permeate flux of 30 L h^{-1} m^{-2}.

3.2. Influence of sequencing high aeration rate/low aeration rate

A variation of the gas flow rate was tested, alternating high aeration rate ($Q_g = 1.62$ Nm^3 h^{-1}, $U_{gs} = 0.158$ m s^{-1}, $SAD_m = 1.086$ Nm^3 h^{-1} m^{-2}) during a very short time (10 s) with a lower aeration rate ($Q_g = 0.145$ Nm^3 h^{-1}, $U_{gs} = 0.014$ m s^{-1}, $SAD_m = 0.096$ Nm^3 h^{-1} m^{-2}) during the other 290 s. These aeration rates were determined to have exactly the same net air flow rate than for the continuous aeration experiment at 0.195 Nm^3 h^{-1} ($U_{gs} = 0.019$ m s^{-1}, $SAD_m = 0.129$ Nm^3 h^{-1} m^{-2}). Fig. 7 shows that the curve with a 0.195 Nm^3 h^{-1} continuous gas flow rate has not the same shape than the curve presented in Fig. 6. Experiments II and III are not coupled (different sludge samples), but as it was explained before, their characteristics in terms of MLSS and mean particle size were similar. Nevertheless, the two experiments III and IV compared on Fig. 7 are coupled and were realised with the same sludge.

According to Fig. 7, varying aeration was clearly positive to reduce TMP increase. At beginning, the shape of the TMP vs. V curve was exactly the same but above a filtered volume of 4 L, the TMP of the continuous aeration experiment increases with a very high slope to reach 0.7 bar and a fouling velocity of 8×10^{14} m^{-1} m^{-3} after collecting 15 L of permeate. On the contrary, for the experiment with sequencing aeration, the equivalent TMP (after a filtration of 15 L) was only equal to 0.25 bar and the fouling velocity equal

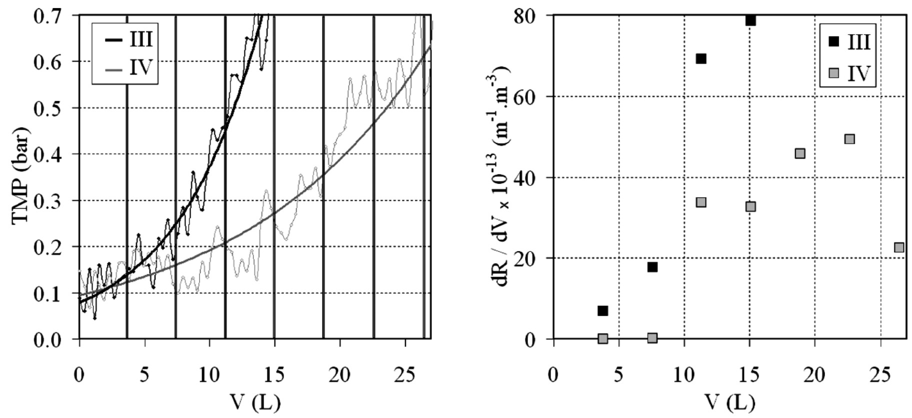

Fig. 7. Comparisons in term of fouling between discontinuous and continuous aeration for the same net air flow rate $Q_{g\ net} = 0.195$ Nm^3 h^{-1}, $J_p = 30$ L h^{-1} m^{-2}, $U_{ls} = 0.009$ m s^{-1}. (III) $U_{gs} = 0.019$ m s^{-1}/$SAD_m = 0.129$ Nm^3 h^{-1} m^{-2} (black). (IV) $U_{gs} = 0.014/0.158$ m s^{-1}/$SAD_m = 0.096/1.086$ Nm^3 h^{-1} m^{-2} every 290/10 s (grey). Vertical grey lines correspond to the periods with high aeration rate.

to 3.3×10^{14} m^{-1} m^{-3}. Hence, at a given filtered volume, fouling velocity is always lower for the experiment with discontinuous aeration than for the continuous one. A detailed analysis of the TMP plots showed that the TMP before and after the period of high aeration is almost the same, so the high aeration period reduces fouling but it is observable only on a long filtration period. Concerning the experiment with discontinuous aeration with continuous permeation, there would be a possible competition between the driving force maintaining particles attached to the membrane and the temporary high shear stress induced by the periodic high air flow rate. It seems that a part of the deposit could probably be removed by the shear stress but not the entire cake because particles are still driven away to the membrane by the permeate flow.

3.3. Influence of relaxation periods on fouling

Experiments I and V, respectively with and without relaxation (permeation off) and both with continuous aeration, are given on Fig. 8. The relaxation was during 60 s every 300 s with the same aeration conditions than for the continuous permeation experiment ($SAD_m = 0.129$ Nm^3 h^{-1} m^{-2}).

Considering the $dR/dV = f(V)$ plot (Fig. 8), fouling velocities are similar for the two experiments. However, there is a slight difference in TMP curves after the fifth relaxation period where TMP is lower in discontinuous permeation experiment than the continuous one. During the relaxation period, the TMP is equal to zero but after this period, so when filtration is running again, TMP reach the same value than before the relaxation period. It is then possible to say that the

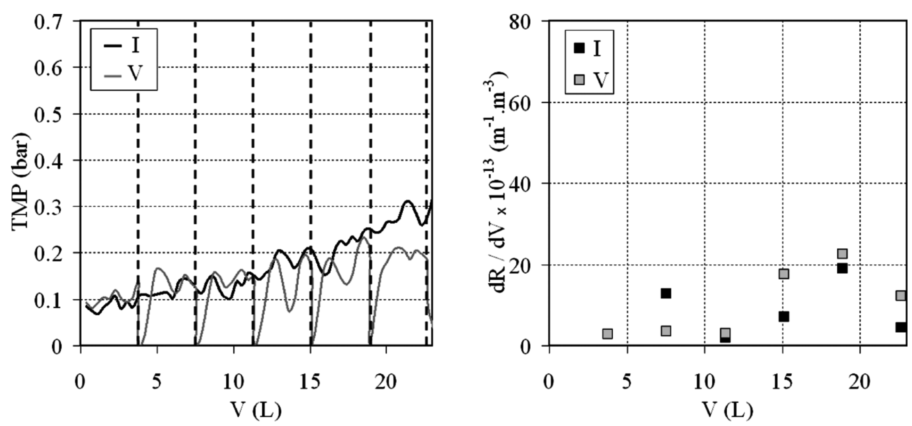

Fig. 8. Comparisons in term of fouling between discontinuous and continuous permeation with continuous aeration $U_{gs} = 0.019$ m s^{-1}/$SAD_m = 0.129$ Nm^3 h^{-1} m^{-2}, $J_p = 30$ L h^{-1} m^{-2}, $U_{ls} = 0.009$ m s^{-1} with (I) continuous filtration (black) and (V) on/off permeation 300/60 s, $J_{p\ net} = 25$ L h^{-1} m^{-2} discontinuous permeation (grey). Vertical black dotted lines correspond to relaxation periods.

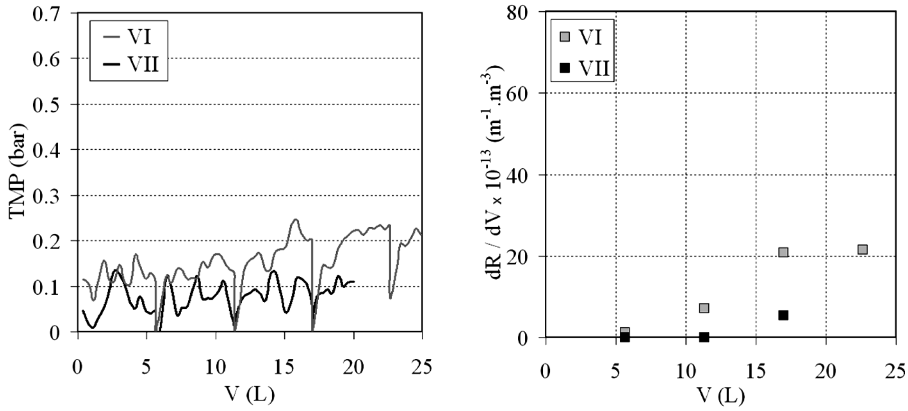

Fig. 9. Comparison in term of fouling between discontinuous and continuous aeration for discontinuous permeation, $J_p = 30$ L h^{-1} m^{-2}, $U_{ls} = 0.009$ m s^{-1} and (VI) $U_{gs} = 0.011/0.079$ m s^{-1}/$SAD_m = 0.073/0.543$ Nm^3 h^{-1} m^{-2}, every 450/60 s on/off permeation (grey line) with (VII) $U_{gs} = 0.019$ m s^{-1}/$SAD_m = 0.129$ Nm^3 h^{-1} m^{-2} and 450/60 s on/off permeation (black line).

effect of relaxation was only slightly observable on short-term experiments but its influence can be more important on long-term experiments.

During relaxation period, the driving force which keeps the particles near the membrane is stopped. Particles could then be removed in the module, and this phenomenon could be enhanced by air and liquid flow rate but these flow rates used here seems to be not sufficient to remove away particles out of the module. The concentration inside the module could thus be possibly constant and particles not further more attached on the membrane but still near.

3.4. *Influence of coupling relaxation period and high aeration*

Two experiments, VI&VII, both with relaxation periods (450/60 s), are compared on Fig. 9, one with a continuous aeration and the other one with a high air flow rate during the relaxation period. The net air flow rate of the two experiments is exactly the same.

It was observed (Fig. 9) that TMP and fouling velocities are lower in the experiment with continuous aeration than in the experiment with combination of high and low air flow rates (Fig. 9). It seems that in the second experiment, the lower air flow rate ($SAD_m = 0.073$ Nm^3 h^{-1} m^{-2}) during the filtration period is not sufficient to maintain low TMP. As a consequence, TMP is increasing and the corresponding fouling velocity too. The influence of periodic high aeration is then non advantageous in comparison to the continuous air flow rate experiment. At equivalent air volume and then air cost and with relaxation periods, it seems preferable to use a higher continuous air flow rate, than a high/low air flow rate combination. The high air flow rate without filtration seems to have been not sufficient enough to counterbalance the rise of pressure during the filtration period.

The coupled discontinuous aeration and relaxation could have complementary effects and their influences could modify fouling together. The specific contribution of each operation cannot be distinguished.

3.5. *Overview of all experimental results*

Net fluxes $J_{p\ net}$ and specific energy consumption for aeration (E_{air}) have been calculated [21] for all the experiments (I–VII) and are presented in Table 3.

Table 3
Net fluxes and specific energy consumption for aeration

Experiment number	I	II	III	IV	V	VI	VII
Aeration	c	c	c	d	c	c	d
Aeration on/off periods (s)				290/10			450/60
Filtration	c	c	c	c	d	d	d
Filtration on/off periods (s)					300/60	450/60	450/60
Net flux J_{net} (L h^{-1} m^2)	30	30	30	30	25	26.5	26.5
Specific energy consumption for aeration E_{air} (kWh m$^{-3}{}_p$)	0.244	0.487	0.244	0.243	0.292	0.276	0.276

c, continuous; d, discontinuous.

Table 4
Fouling results in terms of fouling resistance R and specific cake resistance αC

Experiment number	I	II	III	IV	V	VI	VII
Aeration	c	c	c	d	c	c	d
Aeration on/off periods (s)				290/10			450/60
Filtration	c	c	c	c	d	d	d
Filtration on/off periods (s)					300/60	450/60	450/60
$R \times 10^{-12}$ (m^{-1})	1.0	0.6	7.7	1.3	0.6	1.0	0.9
αC (10^{13} m kg^{-1})	14.4	6.8	84.0	12.5	4.6	3.2	7.7

c, continuous; d, discontinuous.

Specific energy consumptions for the permeate pump are not detailed but are one hundred times lower than energy consumption for aeration. Net fluxes differ slightly and are as expected lower for experiments with discontinuous filtration. E_{air} is the same for experiments III and IV. Operation at high aeration during a very short time (10 s) does not modify the energy demand for aeration. On the contrary, operation with relaxation periods increases the value of E_{air} (experiments V, VI and VII) by reducing the net flux.

Moreover, it is to point out that the mode of operation influences the value of the specific cake resistance αC, calculated [22] between the beginning of the experiment up to a filtered volume of 15 L, and given in Table 4.

There is no clear relationship between energy consumption and cake properties. Continuous filtration induces high cake specific resistance. A lower cake specific resistance for a 15 L filtered volume is obtained when experiments are performed with relaxation (V, VI & VII). Discontinuous permeation and/or aeration have beneficial effects on filtration by decreasing cake and fouling resistances.

At last, permeability (Lp) with pure water was measured at the beginning (Lp_o) and at the end of the experiment. Lp was also measured after a single hydraulic backwash in order to calculate the Lp recovery induced by a single backwash. Irreversible fouling was evaluated by measuring permeability after several hydraulic backwashes to characterise the level of adsorption on the membrane. All these data are presented in Table 5.

Permeability recoveries are lower for continuous experiments (I–III, around 60%) than for discontinuous ones (IV–VII, around 80%), even if no correlation was found with permeability loss values.

A higher air flowrate (II) is better than a lower one (I) to limit permeability loss but no influence of aeration was found in terms of fouling reversibility and irreversibility. It seems that even if a higher aeration rate modifies the cake structure (Table 4), this cake is no more removed by hydraulic backwashes. The first layer of adsorbed foulants on the membrane seems to be the same whatever aeration during filtration.

Concerning intermittence of aeration, discontinuous aeration (IV) limits permeability loss and allows a more easily fouling removal, with less adsorption. This kind of aeration could decrease the adsorption which occurs during the first filtration instants [23–25]. A high air flowrate after 290 s seems to limit this deposit of initial soluble and microbial products on membrane.

The major difference of fouling removal between all experiments is obtained with discontinuous permeation. Relaxation has an influence on cake properties by facilitating cake removal with water backwash

Table 5
Initial, final and after backwash permeabilities and L_p recovery for all experiments

Experiment number	I	II	III	IV	V	VI	VII
Aeration mode	c	c	c	d	c	c	d
Aeration on/off periods (s)				290/10			450/60
Filtration mode	c	c	c	c	d	d	d
Filtration on/off periods (s)					300/60	450/60	450/60
Lp_o at the beginning of the experiment (L h^{-1} m^2 bar^{-1})	450	450	400	450	425	480	465
Lp_o loss (%)	78	62	40	34	69	85	61
L_p recovery after a single backwash with water (%)	58	56	74	80	76	92	77
Irreversible fouling part (%)	16	20	16	9	3	6	8

sequences, with a permeability recovery higher than 76%, and decreasing strongly the adsorption. These results confirm results about cake removal [8] and irreversible fouling [26]. Sequencing permeation seems to modify the gel layer on the membrane by a sequential pressure release. Same results were found with the experiment with association of discontinuous aeration and permeation (VII). The influence of both discontinuous permeation and aeration cannot have been dissociated to discontinuous permeation only and should be studied in details.

4. Conclusions

This study focused on the influence on fouling of discontinuous aeration and permeation in a side-stream membrane bioreactor. Experiments were performed with real sewage, activated sludge from an MBR plant with similar configuration. They were performed for different hydrodynamic conditions.

Firstly, the comparison between two different air flow rates was realised. It was shown that fouling was lower with higher air flow rate but the specific energy high (0.416 kWh m^{-3}). In order to operate at a low energetic cost, different tactics were tested: periodic high air flow rate, relaxation periods and coupling of these two techniques. The periodic high air flow rate with continuous filtration has shown interesting behaviour by maintaining a reasonable TMP (0.3 bar) for a 15 L filtered volume and especially moderate fouling velocities. Relaxation periods have also shown interesting results with low fouling velocities (below 2.5×10^{14} m^{-1} m^{-3}) even if this influence should probably be more observable on long-term experiments. Concerning the coupling of these two techniques, two experiments were compared, one with discontinuous aeration and permeation and the other one with continuous aeration and discontinuous permeation. For these two experiments, TMP and fouling velocities were lower for the experiment with continuous aeration. This was probably due to the too low air flow rate ($SAD_m = 0.073$ Nm^3 h^{-1} m^{-2}) during filtration periods for the experiment with discontinuous aeration. In this experiment, the high air flow rate without filtration was not sufficient to counterbalance the rise of pressure during the filtration period. The relaxation with a sufficient and continuous air flow rate seems to be a good compromise to maintain low TMP and very low fouling velocities (below 5×10^{13} m^{-1} m^{-3}).

Concerning the specific energies, discontinuous experiments were tested under slightly higher energy consumptions but showed very significant positive effects on cake properties as cake specific resistance, reversible and irreversible fouling. Indeed in discontinuous experiments, the permeability recovery was higher and irreversible fouling part lower than for continuous experiments. The structure of the cake which is less dense allows an easier cake removal by a simple backwash with water and relaxation seems to modify adsorption on the membrane.

Discontinuous filtration is a promising method to keep lower TMP and fouling velocities and is more advantageous than discontinuous aeration. Coupling these two methods was tested but first results are not promising. These results are encouraging and longer experiments with continuous feeding and the same operating conditions with permeation sequences will be performed in order to study the evolution of fouling on long-term periods.

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Nomenclature

Symbols

αC	specific cake resistance (m kg^{-1})
A	cross sectional area (m^2)
D	diameter (m)
E_{air}	specific energy consumption for aeration (kWh $m^{-3}{}_p$)
J_p	permeate flux (L h^{-1} m^{-2})
MLSS	mixed liquor suspended solids (g L^{-1})
P	pressure (bar)
Q	flowrate (Nm^3 h^{-1})
R	fouling resistance (m^{-1})
SAD_m	membrane specific aeration demand (Nm^3 h^{-1} m^{-2})
SAD_p	permeate specific aeration demand (Nm^3 $m^{-3}{}_p$)
SRT	sludge residence time (day)
TMP	transmembrane pressure (bar)

Subscripts

b	bundle
c	cartridge
g	gas
i	inlet

l	liquid
m	membrane
o	outlet
p	permeate

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