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Aeration and hydrodynamics in submerged membrane bioreactors

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A B S T R A C T

Membrane bioreactor (MBR) is already a well-developed wastewater treatment process for both municipal and industrial applications. Nonetheless, membrane fouling remains a significant problem for its wider development. In the case of submerged membrane bioreactors (SMBRs), one of the most efficient strategies to limit fouling is the use of a gas/liquid two-phase flow to enhance the mass transfer. However, the effect of aeration still remains incompletely understood. The complexity of flows and of the nature of activated sludge makes a theoretical approach difficult. Aeration is the source of a large part of the operating costs in most industrial scale plants and its optimization is a necessity to make the process really efficient. This paper first deals with hydrodynamics in MBRs, then it reviews the parameters of aeration and their impact on filtration performance. Finally, the effects of aeration mechanisms on biological media are described.

Keywords:

Submerged membrane bioreactor
Fouling
Hydrodynamics
Aeration
Energy saving

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0. Introduction

MBR is a wastewater treatment process which combines biological treatment and physical separation by membrane filtration in one step only. It has numerous advantages over the conventional activated sludge process (CASp), i.e., more constant permeate quality, independent control of solid and hydraulic retention times, operation at higher mixed liquor suspended solids concentration and most of the time sludge production reduction [1]. This process has generated a real scientific interest and more than 800 scientific articles dealing with MBRs for wastewater treatment have been published between 1997 and 2007 [2]. MBR process is more complex than conventional ones, needing membrane maintenance and higher capital outlay for equipment while also having higher operating costs. Nevertheless MBR technology has seen strong growth over recent years due to the good quality of the produced water. The global market is expected to increase from US\$ 296 million in 2008 to US\$ 488 million by 2013 [3]. Lesjean and Huisjes [4] studied the evolution of the European market until 2005 and found a non-negligible increase in the number of installations, particularly since 2002. In 2005, although the municipal sector was made up of fewer installations, it represented about five times the surface area of the industrial sector and consequently generated the largest part of the market. This is related to the viability of large municipal plants owing to the successful introduction and commercialization of the immersed configuration (SMBR, submerged membrane bioreactors). Similar trends are observed on the Chinese market [5]. However, one of the main drawbacks regarding the widespread use of MBR is membrane fouling. This is one of the key points for the development of the process and the number of publications linked to this topic has increased rapidly (Fig. 1). The other key point is probably membrane material: membrane module costs, and consequently capital costs, have significantly decreased over the last years. Given the great variety of membrane materials and the widespread use of MBR, interactions between membrane materials and the pollution or sludge constituents are numerous, leading to research topics on fouling-reducing membrane material.

The effects of membrane materials and characteristics as well as those of sludge and operating parameters on fouling have recently been reviewed [6–8].

Besides controlling and optimizing these parameters, the management of hydrodynamic conditions in MBRs may be a solution to limit fouling. It has already been investigated with the use of gas bubbling which is now well known to improve filtration performance. However aeration can require a great proportion of the energy used to run the process, particularly in SMBRs [9,10]. The latter reviews mentioned above [6–8] briefly tackled the issue of

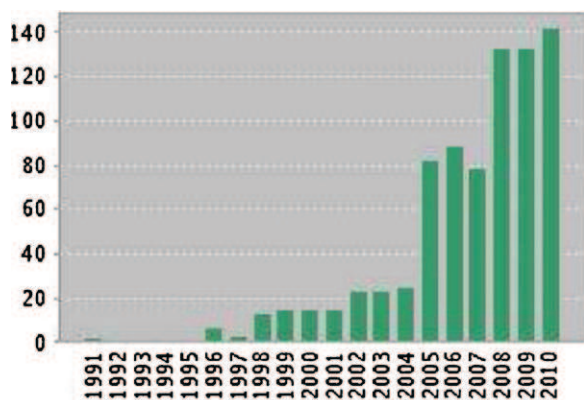


Fig. 1. Number of published items dealing with the topic “bioreactor membrane fouling” since 1991 (ISI Web of Knowledge, 2010).

hydrodynamics and aeration in MBRs but did not focus on it. The use of gas bubbling to enhance the membrane process was the subject of a previous review by Cui et al. [11]. Some improvements have been made since its publication. For instance, the local characterization of two-phase flow has been made more accurate by the development of techniques such as computational fluid dynamics (CFD) or particle image velocimetry (PIV), so that previous results should be completed.

The present paper follows Cui et al. [11] work. It focuses on hydrodynamic conditions and the use of air sparging in the particular case of SMBRs. The effect of hydrodynamics in SMBRs is reminded, including design considerations such as fibre size or packing density. The effect of aeration through operational parameters is then reviewed. Considering hydrodynamic issues, the reported conclusions may be applied to any other submerged filtration systems, such as drinking water treatment processes. Finally, the paper considers the explanation of the effect of hydrodynamic operating parameters on fouling, based upon the study of local-scale phenomena such as fibre movements and the influence of shear induced by two-phase flows.

1. Filtration hydrodynamics

Filtration flux has often been reported as the main parameter which controls membrane performance [12–14]. The best way to manage flows to limit fouling is not obvious and several concepts have been created and improved on. They have already been reviewed [15,16].

Fouling mechanisms are usually described in three stages for constant flux operation mode [6,17] which can be seen in Fig. 2:

- A fast but short rise in trans membrane pressure (TMP): conditioning fouling. Strong interactions, among which adsorption, between the membrane surface and colloids, including EPS, cause initial fouling and pore blockage.
- A long period during which TMP increases slightly: slow, steady fouling. The particles settle on the membrane surface and form the cake layer. The duration of the second step, or sustainability time, depends on the permeate flux [18] (Fig. 3).
- A very strong rise of TMP: TMP jump. During the previous step permeability is not much affected but fouling is not uniform. Some areas suffer stronger fouling because of flux heterogeneities along the membranes. This is a self-accelerating phenomenon, which leads to exponential fouling. TMP jump could also be induced by a sudden change in the biofilm developed in the membrane [19].

Hydrodynamics homogeneity appears to be of prime importance when MBRs need to be managed efficiently. Homogeneous

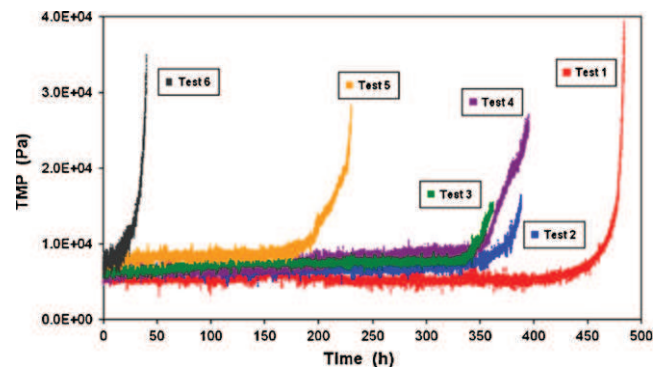


Fig. 2. Variation of TMP with various filtration fluxes [18].

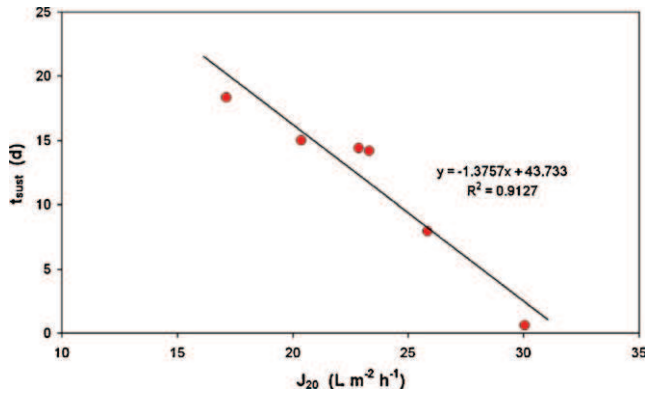


Fig. 3. Correlation between sustainability time and permeate flux [18].

hydrodynamic conditions would enable to limit fouling and many works have dealt with this key point.

1.1. Flux heterogeneity

A serious drawback of hollow fibre membranes is the internal pressure drop caused by permeate suction. TMP is higher at the output of a hollow fibre (where permeate is drawn). Therefore the local flow is stronger in this part and may be higher than the critical flux, which will result in faster fouling there [20]. To maintain a constant flux, it is necessary to increase the TMP but, in that case, fouling spreads to the other end of the fibre [21]. The mechanism is described in Fig. 4 [22]. It is therefore essential to limit the axial pressure losses along fibres to avoid an uneven distribution of filtration and faster fouling.

The heterogeneity of fluxes also influences fouling at bundle scale. The individual contribution of each hollow fibre to filtration performance has been experimentally investigated in a square bundle with 3 fibres on each side and one in the centre [23]. Rather low fluxes were imposed which led to slow and thus observable fouling phenomena. The average fluxes presented a difference of about 25% after 180 min of filtration (21, 18 and 15 L m⁻² h⁻¹ for the corner, side and centre fibres, respectively). This mal-distribution was linked with fouling behaviour. As shown in Fig. 5 the increase of TMP just followed the increase of standard deviations of individual fibre fluxes. It was found that an increase in the standard deviation of fluxes above about 0.20 caused the TMP to increase significantly.

To explain the flux heterogeneity and the poor performance of the central fibre, two mechanisms were proposed: “bundle resistance”, which is related to the mechanical resistance of the bundle without filtration, and “permeate competition”, which accounts for the negative effect of filtration by neighbouring fibres. To evaluate the effect of these mechanisms, the hydrodynamic resistance

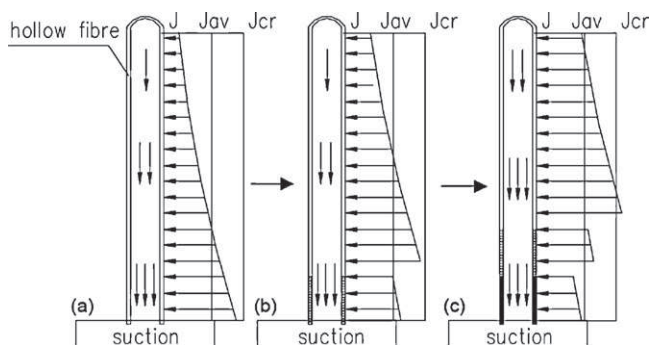


Fig. 4. Flux mal-distribution along a hollow fibre over time, where J is the local flux, J_{av} the average flux and J_{cr} the critical flux [22].

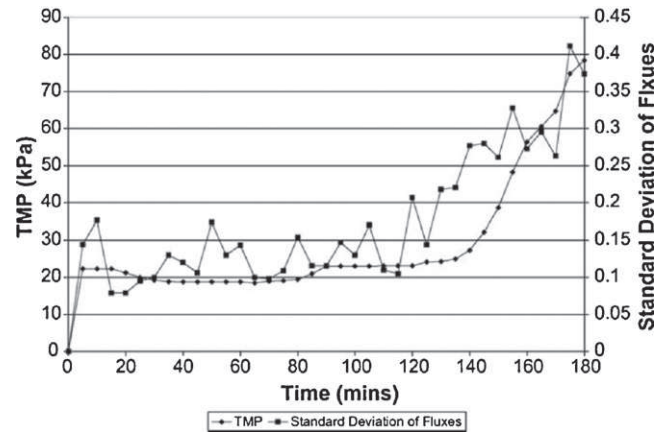


Fig. 5. Variations of TMP and of standard deviation of flux [23].

(which added to the intrinsic resistance of the membrane gave the total resistance in the “resistance-in-series” model) of fibres was calculated. To separate their effect, the hydrodynamic resistance of the central fibre was evaluated with and without suction of the other fibres. The hydrodynamic resistance of the centre fibre was between 3.4 and 4 × 10¹² m⁻¹ whereas that of the other fibres was lower than 2 × 10¹² m⁻¹ when all the fibres were operated. However, it was nearly the same when the centre fibre was the only one to filtrate. This showed that the “permeate competition” had a predominant effect on “bundle resistance” with respect to filtration performance. The authors suggested that many spaced subunits could improve performance.

In a further work, a system was developed to monitor this heterogeneous permeate flux distribution at the module scale [24]. The SMBR was made of five mini bundles representing different regions of the module. Each bundle was composed of 10 hollow fibres. Constant temperature anemometry (CTA) probes were used to evaluate the permeate velocity at each bundle outlet. A different trend was observed at the module scale compared to the bundle scale. Two experiments were made: one with five clean bundles and one with a pre-fouled bundle. In the first experiment, all the bundles had similar behaviour whereas, with the “used” bundle configuration, notable standard deviations between fluxes were observed. The monitored TMP was similar for both experiments. In this case, heterogeneity in flux distribution could not be related to a fouling increase. Nonetheless, the authors concluded that global TMP history could not indicate fouling nor flux mal-distribution. Thus there was a need for this local monitoring of system performance. It enabled to detect local fouling or blockage but also failure of aeration (see Section 2.2).

1.2. Packing density

The fact that flux heterogeneities inside hollow fibre bundles influences filtration performance implies that packing density is of great importance. In a SMBR lowering the packing density from 44 to 28% led to a marked improvement [25]. It was believed to be due to the way cake builds up on the fibre. Some of the fibres could get stuck together as their cake layers merge. These fibres would then foul rapidly, while the other fibres would not foul as rapidly. This merging of cake layers has been observed in early studies when filtering activated sludge alone [26].

Similar results were found in another study where too high a packing density (57 fibres cm⁻² with an external diameter of 0.72 mm) led to rapid fouling [27]. Dividing the fibre density by 10 enabled more viable fouling rates to be reached. Other authors have observed the appearance of dead zones and sludging in the

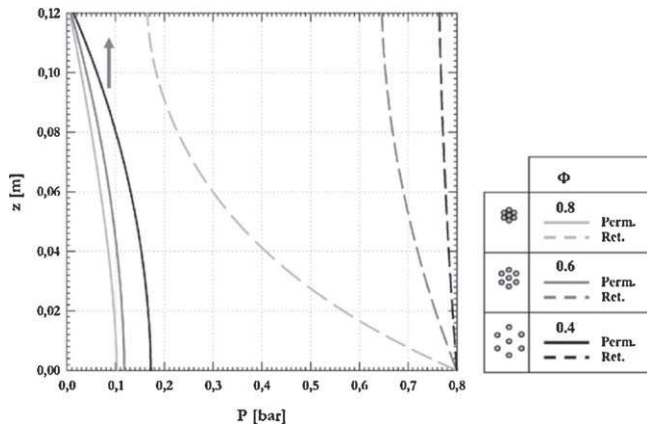


Fig. 6. Pressure profile on permeate and on retentate sides depending on packing density [30].

centre of hollow fibre bundles, depending on the bundle diameter and packing density [28].

More recently CFD enabled to provide more insight to this problem of packing density. CFD gives access to values of local parameters which are difficult to measure and, in a shorter time and for a lower cost, provides results that would otherwise require extremely impractical experiments (e.g. fluid flows inside membrane pores). It has been widely used to model membrane processes and its application has been reviewed in 2006 [29]. In 2010 a CFD model was developed with the finite element code COMSOL multi-physics to study the packing density of hollow fibres [30] by solving the Navier Stokes equations. The pressure profiles obtained with the model for both permeate and retentate sides are shown in Fig. 6. Filtration flux was calculated and compared with experimental results (Fig. 7).

An increase in packing density led to a more heterogeneous permeate profile along the fibre length and consequently to a strong decrease of the filtration flux per surface area of the membrane. Thus a compromise must be found regarding packing density between a higher filtration surface area (and its consequent permeate production) and the loss of performance per surface area. In this study, a packing density between 0.5 and 0.6 (on the elbow of the curve) would give a good compromise.

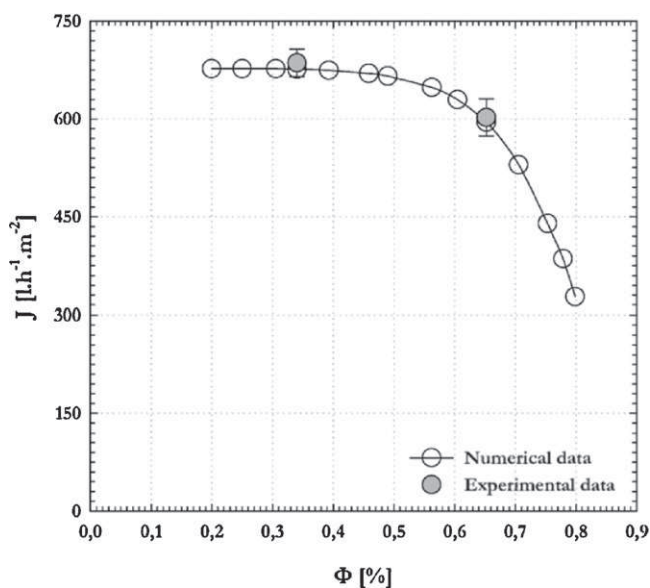


Fig. 7. Influence of packing density on filtration performance [30].

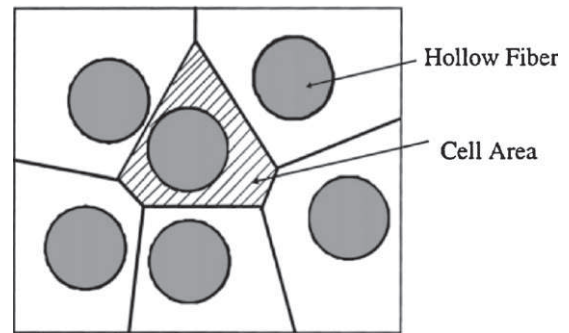


Fig. 8. Example of Voronoi tessellation [32].

However, the bundle was modelled as a perfect arrangement of regular cylinders and the effect of random packing was neglected. This factor should be taken into account as heterogeneity of fluxes is a prevalent mechanism in fouling. To the best of our knowledge, this has not been done with MBRs but some publications deal with this approach regarding hollow fibre contactors. Voronoi tessellation has been used to develop models [31–34]. Straight boundaries are set between neighbours, which are equidistant from each other (Fig. 8). Consequently each fibre is in a polygonal cell and the entire space is taken into account.

The models showed that random packing had a serious effect on flow mal-distribution in membrane contactors. Moreover, the increase in packing density led to a decrease in mass transfer coefficients. A similar approach would provide a means to simulate the hydrodynamic conditions in hollow fibre bundles more accurately and define the most suitable packing density.

1.3. Filtration sequencing, backwash and relaxation

Most of the papers mentioned in this paragraph are reported in Table 1 with detail of the main operating conditions of the studied processes.

A solution to manage the hydrodynamics is filtration sequencing through operational parameters. Backwashing consists of reversing the flow of permeate in order to limit membrane fouling. This method requires production stop and permeate reuse. Backwashing is a solution to limit membrane fouling but it remains expensive in time and energy, and risky for membrane integrity.

The introduction of a relaxation time when the filtration is stopped makes back-transport easier by ending the convective flow. Hong et al. [35] managed to improve their MBR performance with intermittent filtration.

Nonetheless long and frequent relaxation could cause fouling because of the high instantaneous fluxes needed to maintain water production [14]. Various filtration modes (continuous, relaxation and backwash) were tested with the same average flux ($20 \text{ L m}^{-2} \text{ h}^{-1}$). It induced instantaneous filtration fluxes of $22 \text{ L m}^{-2} \text{ h}^{-1}$ for relaxation sequences and $25 \text{ L m}^{-2} \text{ h}^{-1}$ for backwash ones. The resistance of the upper layer of the cake (consisting predominantly of loosely bound biomass flocs and attached soluble microbial products (SMP)) strongly depended on instantaneous fluxes and on the resulting compression of this layer. Consequently fouling rates were higher with relaxation and even worse with backwash than with continuous filtration.

The fact that relaxation is more efficient than backwash has been confirmed elsewhere [36]. However, the relaxation mode was more efficient than the continuous one. In the studied configuration relaxation was effective to control fouling by reducing the cake layer which had a non-negligible fouling contribution. It should be noted that the instantaneous fluxes were close to those of the

Table 1
Influence of sequencing on filtration performance.

Reactor volume (L) Membrane surface area (m ²)	Effluent type	J J_b (L m ⁻² h ⁻¹)	MLSS (g L ⁻¹)	Filtration sequencing	Observations	Refs.
3.5 FS 0.106	Simulated sewage	10–25 –	6.8–8.8	8 min F/15 s–4 min R	The residual fouling rate increased exponentially as relaxation time decreased. Fouling was eliminated by filtrating below the critical flux (22 L m ⁻² h ⁻¹) with relaxation time of 4 min for 8 min of filtration.	[38]
3.5 FS 0.106	Simulated settled sewage	10–28	6.8–21.1	8 min F/2 min R	Intermittent permeation allowed long-term operation. Combined with aeration, it enabled the MBR to be operated above critical flux, with a variable throughput.	[39]
30 (aeration and membrane tank) HF 0.3	Synthetic wastewater	20–40 34	5.5	Continuous 220 s F/20 s R 220 s F/20 s B	Continuous mode was the most efficient filtration mode because of the lower instantaneous fluxes induced. They strongly influenced the formation of the upper cake layer and its compression.	[14]
7 HF 0.25	Synthetic wastewater	20–34 30–50	9–10	Continuous 220–480 s F/20–40 s R/20–40 s B	Relaxation was more effective than backwash because of lower instantaneous fluxes. It was more effective than continuous filtration for close instantaneous fluxes. Relaxation removed solids (cake layer) and, to a lesser extent, irreversible fouling (SMP) but it was not effective against pore clogging.	[36]
230 HF 0.9	Screened raw domestic wastewater	20 39	6.6–6.8	5–60 min F/0–20 s B	The cake layer resistance decreased by a factor of 1.63 with an optimal sequence of 15 s of backwash every 10 min of filtration. These sequences were effective in reducing fouling caused by cake layer formation and pore blocking.	[40]
57.6 FS 0.7	Synthetic wastewater	16.7–33.3 –	7.4	10 min F/2–10 min R	Critical flux determined by a stepwise method at 44–47 L m ⁻² h ⁻¹ . Continuous mode was more efficient because of the lower instantaneous flux. High instantaneous flux induced higher pore clogging resistance and consequently higher fouling rate.	[41]

Abbreviations: MLSS, mixed liquor suspended solids; HF, hollow fibre; FS, flat sheet; J, filtration flux; J_b , backwash flux; F, filtration; B, backwash; R, relaxation.

study mentioned above (between 20 L m⁻² h⁻¹ and 22 L m⁻² h⁻¹ depending on the sequencing).

Filtration sequences with various fluxes have also been tested. Metzger et al. [14] tried a mixed mode with different permeate flux: 40 L m⁻² h⁻¹ for 80 s and 20 L m⁻² h⁻¹ for 340 s. They found that this mode induced the highest fouling rate, compared to continuous, relaxation and backwash ones, because of higher instantaneous fluxes. In contrast, Wu et al. [37] found that this technique could be used to improve MBR performance. They tested various sequences with high flux (40–60 L m⁻² h⁻¹) followed by filtration at a lower flux (10.3–22.3 L m⁻² h⁻¹) for various durations, keeping the same median filtration flux (20 L m⁻² h⁻¹). These mixed modes were more efficient than conventional ones, with an optimal sequence of 120 s of filtration at 60 L m⁻² h⁻¹ and 290 s at 10.3 L m⁻² h⁻¹. The authors suggested that a cake layer acting as an SMP filter was formed during the high flux step. Then the fouling proceeded very slowly and this layer remained loose. This meant that it could be removed during the backwash step, with the entrapped SMP.

1.4. Conclusion on filtration hydrodynamics

If it is known that the filtration flux has a non-negligible impact on membrane fouling, recent studies highlighted the influence of the flow distribution upon MBRs performances. Permeate flux

mal-distribution has early been observed along fibre length. More recently this phenomenon has been investigated in the depth of fibre bundles. Besides the development of local monitoring systems, CFD modelling could be used to tackle this issue. Module configuration, through packing density, was found to impact on permeate flux profile along the fibre. Design considerations are closely linked with local filtration performances. Thus a compromise must be found between a sufficient space between fibres (low density bundle) and a large surface of filtration (high density bundle). Given the importance of hydrodynamics homogeneity a next step would be the modelling of random packed modules to simulate more accurately SMBRs and further improve their performances.

Filtration sequencing is another solution to run SMBRs efficiently. Although the average filtration flux must be considered for economical reasons, the instantaneous flux really impacts on filtration performances. It depends on filtration, relaxation and backwashing times. Hence backwashing can be very effective to remove fouling but needs too high instantaneous flux to maintain the water production to be profitable. Relaxation generally presents an interest but it can already be seen in Table 1 that operating conditions vary widely from one pilot to another. The contradictory results found with relaxation [14,36] while the instantaneous fluxes imposed were nearly the same highlight the difficulty to draw conclusions. The efficiency of filtration sequencing depends

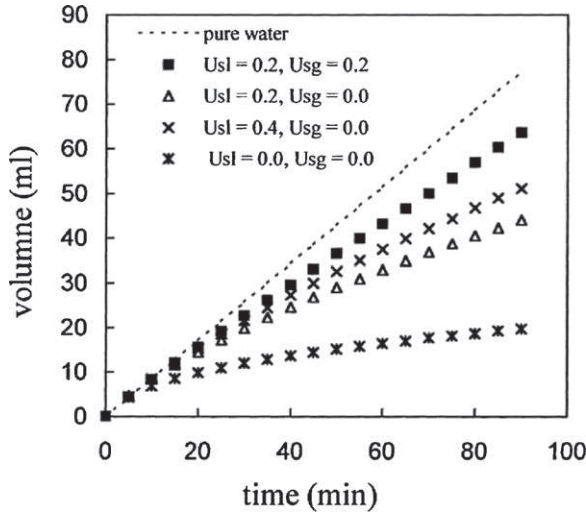


Fig. 9. Effect of bubbling on permeate production [42].

on each MBR configuration and operating parameters but also on the pollution composition (and the sludge quality it induces) and on the aeration usually imposed to remove fouling.

2. Global effect of aeration on fouling

In the previous section, hydrodynamic parameters used to control fouling were presented. The process performance could be further enhanced with the use of air sparging. For instance, combined liquid and gas flow has been shown to have more effect on fouling than a liquid flow with higher velocity [42]. Fig. 9 presents the permeate volume produced after 90 min of filtration in a hollow fibre SMBR. U_{sl} and U_{sg} are respectively the superficial liquid and gas velocities (m s^{-1}). Permeate volume was 30 and 20% higher with bubbling than for single flow filtration which shows the beneficial effect of air sparging. Its use has been the subject of many studies but the management of permeate flux and aeration flow remains a fundamental aspect for the improvement of MBRs.

An early study about energetic expense in MBRs (2000) pointed out the importance of aeration in SMBRs [43]. Because of the need for scouring in SMBRs, both coarse and fine aerators are required. In consequence, the cost of aeration in submerged systems was found to represent more than 90% of the total costs. More recently the main operating conditions of SMBRs were summarised by Melin et al. [44]. They compared several references and found a value of energy consumption per unit volume of produced permeate between 0.2 and 0.4 kWh m^{-3} with respective consumptions of 80–90% for membrane aeration and 10–20% for pumping for permeate extraction. Aeration is the main operating cost in SMBRs and its significant consumption of energy accounts for the numerous scientific articles which deal with this topic.

Aeration used for MBRs has three main roles: to provide oxygen to the biomass, to maintain the activated sludge in suspension and to limit membrane fouling. Most of the time, aeration for biomass oxidation and fouling prevention are separated. The latter is a key parameter for the enhancement of MBR performance and this section focuses on it. The main issues being dealt with are gas velocities, bubble characteristics (size, shape and frequency), aeration design and its homogeneity.

2.1. Characteristic parameters

Besides the injected airflow, Q_g , aeration in an MBR is generally quantified by one of the following parameters:

- Aeration intensity or superficial gas velocity U_g (m s^{-1}):

$$U_g = \frac{Q_g}{S_r} \quad (1)$$

This parameter is quite conventional for gas/liquid characterization, and other parameters specific to SMBRs are frequently used in the literature:

- Specific aeration demand in $\text{m}^3 \text{h}^{-1} \text{air m}^{-2}$ membrane area:

$$\text{SAD}_m = \frac{Q_g}{S_m} \quad (2)$$

- Specific aeration demand in $\text{m}^3 \text{h}^{-1} \text{air m}^{-3} \text{h}^{-1}$ permeate product:

$$\text{SAD}_p = \frac{Q_g}{S_m J} = \frac{Q_g}{Q_p} \quad (3)$$

where Q_g and Q_p are the flows of gas and permeate respectively, J is the permeate flux ($\text{L m}^{-2} \text{h}^{-1}$), S_m is the membrane surface area (m^2) and S_r is the cross-sectional area of the module (m^2).

SAD_p is particularly useful for industry. It provides the specific energy demand for the aeration of the membrane (E_a , in $\text{kWh m}^{-3} \text{permeate}$) to produce permeate and is therefore a direct indicator of the MBR energetic performance [45]. For a given aerator system at a fixed depth in the tank, SAD_p relates directly to specific energy demand for membrane aeration:

$$E_a = k \text{SAD}_p \quad (4)$$

where

$$k = \frac{pT\lambda}{2.73 \times 10^5 \zeta(\lambda - 1)} \left[\left(\frac{10000y + p}{p} \right)^{1-(1/\lambda)} - 1 \right] \quad (5)$$

where p is the blower inlet pressure in Pa; T is the air temperature in K; ζ is the blower efficiency; λ is the aerator constant (~ 1.4) and y is the aerator depth in m.

On most real-scale operational MBRs, SAD_p generally exceeds 10 and can reach 50 [1]. Pollet [46] gathered similar values with most SAD_p between 10 and 25, and a maximum of 65. These values are more variable for lab-scale MBRs, being between 0.002 and 280 [46] and comparisons between experiments may require very precise information regarding the experimental context. The data given in the publications usually enable SAD_m or U_g to be calculated. This is used in addition to Q_g to compare the results of the various experiments. These parameters provide information to quantify the energy demand to run the process but it is also useful to have order of magnitude of the energy costs of SMBRs.

They were assessed in a pilot scale SMBR [9]. The SMBR was composed of 10 flat-sheet membranes with a total area of 16m^2 . It was run at two fluxes: 19 and $25 \text{L m}^{-2} \text{h}^{-1}$. The respective energy demands were 6.06 and 4.88kWh m^{-3} . In each case, the coarse bubble aeration required the biggest proportion of energy consumption and represented almost 50%. Rather high productivity costs were found which was due to the fact that experiment was run at pilot scale, which is not economically viable.

Similarly, in a full scale SMBR, coarse bubble aeration was the largest consumer but to a smaller extent (35%) [10]. However, the authors noted that the overall filtration process (including electrical heating, permeate extraction, tank cleaning in place and compressors for the activation of valves) was very costly in energy, with 56% of the total energy consumption, and that care should also be taken to deal with this point. The SMBR consumed 0.64kWh m^{-3} of permeate, which was higher than the cost of a CASP running in the same city (0.19kWh m^{-3}) but lower than the values the author found in the literature for other full scale MBRs, ranging from 0.8 to 1.2kWh m^{-3} .

A slightly wider range was stated in a review on the state of science in MBR for wastewater treatment with value of energy between 0.5 and 2.5 kWh m⁻³ [2]. The authors precised that this demand could be twice this of CASP (the paper was written in 2007) but that MBR had to be compared with a system that could produce the same effluent quality.

Besides comparing MBR with other processes, MBR plants should be compared with each other. Energetic costs were calculated for each operating equipment of MBRs for the development of a benchmark simulation [47]. The authors found respective values of 0.019 and 0.025 kWh Nm⁻³ of air for coarse and fine bubble aeration whereas the pumping energy factor for permeate was set at 0.075 kWh m⁻³ based on values from MBRs plant. Same order of magnitude has been provided by Racault et al. [48] regarding aeration of municipal MBR plants: they worked on three hollow fibre SMBRs and found a range of energy consumption between 0.013 and 0.024 kWh Nm⁻³ of air whereas it was 0.008 kWh Nm⁻³ of air for a flat sheet SMBR. It should be noticed that in this work a part of the air provided to limit fouling also contributed to biomass oxygenation.

This highlights the difficulty to estimate the energetic costs in SMBRs. Specific costs for aeration can be twice higher from one plant to another one and no reference value could be provided. Nonetheless the papers mentioned above give an order of magnitude of these costs and emphasize the importance of tackling the problem of aeration energetic consumption in SMBRs.

2.2. Aeration homogeneity and design

As seen previously homogeneity of the hydrodynamics is important and it may depend on good design of the aeration system [28]. Nguyen Cong Duc et al. [49] faced a problem of aeration homogeneity in their SMBR. A circulation loop appeared leading to the creation of a dead zone at its centre (Fig. 10).

The holes of the aerator did not all distribute the same amount of gas. The pressure drop due to air friction on the inner surface of the vent tube made aeration control difficult. If friction was too strong, the holes near the air intake distributed almost all the gas. Conversely, if the input pressure of the air was strong enough to prevail over frictional forces, the holes far from the air injection ejected more gas (Fig. 10). Kinetic energy and viscosity must be balanced.

Mayer et al. [50] recommended the use of complex systems provided with numerous holes, which would make the air distribution more homogeneous and thus more effective. Another solution was to confine the air bubbles near the fibre instead of letting them diffuse in the hollow-fibre SMBR [51]. In a further study, the confinement of bubbles was also used to control fouling in a submerged hollow fibre module [52]. A pipe of 2 cm diameter was used to surround 12 hollow fibres of 0.7 mm outside diameter. It kept the bubbles close to the membrane surface, thus using the energy provided to the system more effectively. Moreover, this configuration created slug flow on the outer surface of fibres. The results were compared to those of a similar study [53] where fibres were not confined. At the same feed concentration (5 g L⁻¹), with same nozzle size (1 mm), with a higher filtration flux (36 L m⁻² h⁻¹ instead of 30 L m⁻² h⁻¹), the module that confined the bubbles provided an average TMP increase of 0.02 kPa min⁻¹ against a rate of 0.07 kPa min⁻¹ for the other module with a smaller SAD_m (1.7 m³ m⁻² h⁻¹ against 11.7 m³ m⁻² h⁻¹). Although results should be compared on a more similar configuration (same fibre length and number), this comparison helps to quantify the efficiency of the tested configuration. Confining bubbles close to the fibres, besides making it possible to create slug flow, appears to be a solution to limit fouling in the submerged hollow-fibre configuration.

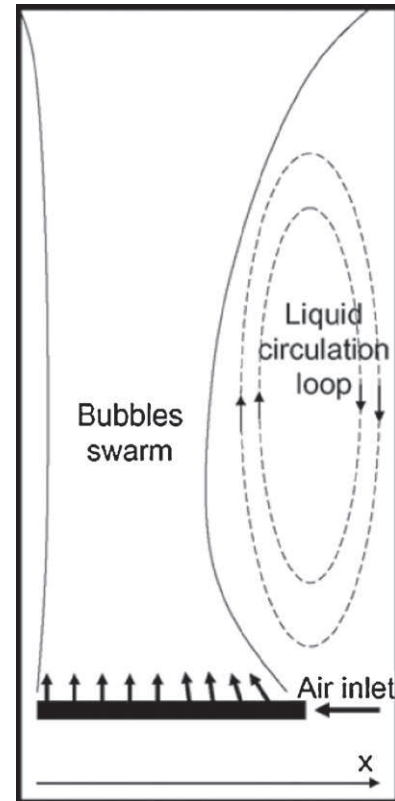


Fig. 10. Aeration heterogeneity in a SMBR [49].

CTA sensors (see Section 1.1 for a description of the system) were used to evaluate the effect of aeration homogeneity on permeate flux distribution [24]. Permeate flux profiles were evaluated for two kinds of aeration conditions during the filtration of bentonite at 2 g L⁻¹: even distribution with all the bundles aerated (Fig. 11) and uneven distribution with only one bundle aerated (bundle 3 in Fig. 12).

TMP was evaluated during a filtration experiment that lasted 180 min. The TMP profiles of the two experiments overlapped for 30 min but, after that, the TMP for the unevenly aerated module was higher than that of the evenly aerated one, with a maximum deviation of 25%. These results confirm that aeration homogeneity enhanced the distribution of permeation fluxes, and is consequently a tool for fouling prevention. Moreover the authors suggested that sensors such as CTA could be used to monitor the permeate flux distribution and provide early warning of fouling or blockage.

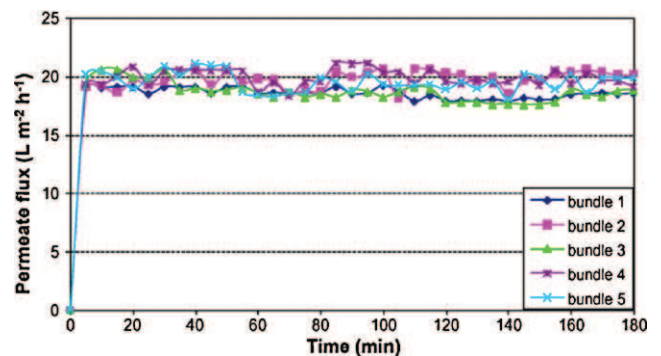


Fig. 11. Permeate flux profile in an evenly aerated system [24].

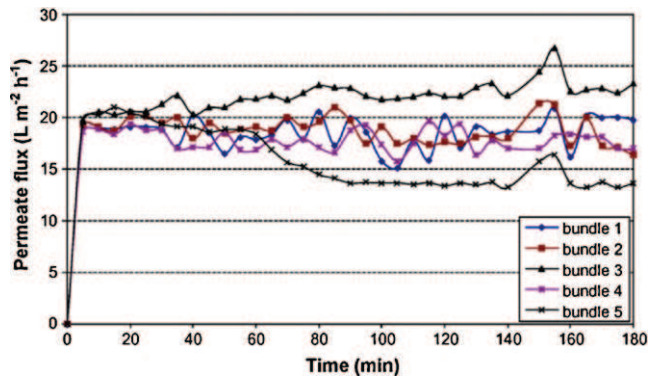


Fig. 12. Permeate flux profile in an unevenly aerated system [24].

The development of CFD enables a more performant approach to tackle this problem of design configuration and avoid design problems such as prevention of dead zones or aeration homogeneity. A 3-phase flow model was developed to improve the design of a real scale hollow fibre SMBR [54]: enlargement of the tank size led to an increase of the mixed liquor and air velocities by 50%.

In another work Lee et al. [55] found a high correlation between local TMP distribution and bio-cake porosity. In consequence, they advised placing the aerator device near the bottom suction of the hollow fibre module because that is where local porosity of the bio-cake is the smallest.

Another solution proposed to improve the air sparging efficiency was to superimpose a pump (and consequently liquid circulation) on the two-phase flow [56]. This led to higher permeation fluxes than with an airlift system. It improved the gas distribution around the fibres and resulted in a more stable, regular slug flow. This showed that homogeneity of the aeration could play a key role in improving the operation of submerged hollow-fibre bundles. However for a U_g value of 0.4 m s^{-1} increasing liquid velocity from 0.2 to 0.4 m s^{-1} in tight fibres configuration and from 0.4 to 0.6 m s^{-1} for loose fibres induced a decrease of final flux obtained after 2 h of filtration. The negative impact of high liquid velocity was confirmed in a later study [57]. Imposing a strong background flow could damp the turbulence imposed by the bubbles. High axial flow (0.16 m s^{-1} against 0.016 m s^{-1}) induced a decrease of standard deviation of shear stresses and the authors found that it can have a detrimental effect on filtration performances.

2.3. Air sparging efficiency: influence of airflow rate

The aeration flow Q_g is a basic parameter for the management of aeration. It has a noticeable influence on fouling and must be reduced to limit running costs. A wide range of experiments have been done to study its effect on MBRs and some publications are listed in Table 2 with the main operating conditions of the studied processes.

Ueda et al. [58] found that air injection reduced fouling in SMBR up to a critical flow rate ($0.7 \text{ m}^3 \text{ min}^{-1}$) corresponding to a SAD_m of $0.25 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$. Beyond this value, increasing airflow did not have a greater effect on TMP, which was linked with the cake removal efficiency. When Chua et al. [38] filtered a suspension in which MLVSS was 15 g L^{-1} , the fouling rate decreased exponentially when the superficial gas velocity increased from 0.02 to 0.15 m s^{-1} . Delgado et al. [59] obtained the same behaviour of the fouling rate against mean shear intensity due to air-sparging. These results highlight the existence of a threshold value for airflow rate beyond which no improvement in filtration can be reached.

The existence of a threshold value or a plateau could be linked to the fact that the rising velocity of bubbles is not proportional to air-

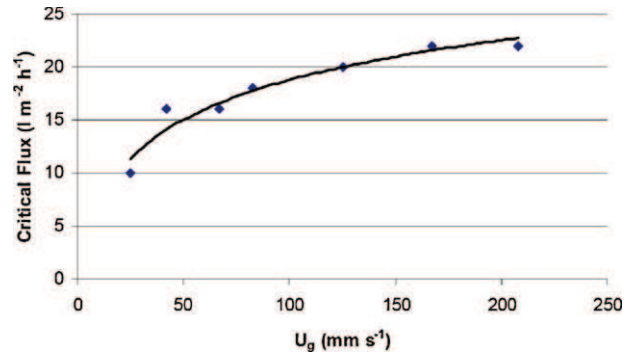


Fig. 13. Variation of critical flux with superficial gas velocities [39].

flow rate. In a pilot scale SMBR Sofia et al. [60] found that, beyond a certain value, the effect of increasing airflow rate on the cross flow velocities of bubbles was insignificant. They thus obtained a maximum bubble velocity of 0.69 m s^{-1} for an optimal U_g of 0.017 m s^{-1} . In an SMBR with hollow fibres, the rising velocity of bubbles was found to increase by 34% when the airflow was increased from 20 to $50 \text{ Nm}^3 \text{ h}^{-1}$ and by 6% when switching from 50 to $90 \text{ Nm}^3 \text{ h}^{-1}$ [49]. To give an order of magnitude, the measured values of velocity were 1.14 and 1.80 m s^{-1} for airflows of 20 and $90 \text{ Nm}^3 \text{ h}^{-1}$ respectively, corresponding to SAD_m of $0.21 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$ and $0.95 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$.

The beneficial effect of aeration can also be seen through the increase of permeate flux. Le Clech et al. [61] found that increasing the superficial gas velocity always had a positive effect on the critical flux. A suspension of 4 g L^{-1} was filtrated with a submerged tubular membrane. The critical flux increased from 16 to $51 \text{ L m}^{-2} \text{ h}^{-1}$ for superficial gas velocities of 0.07 and 0.22 m s^{-1} respectively. In another study for an MLVSS concentration of 17.15 g L^{-1} and an increase of superficial gas velocities from 0.02 to 0.22 m s^{-1} , the critical flux rose from 10 to $23 \text{ L m}^{-2} \text{ h}^{-1}$ [39]. However, the decrease of aeration efficiency with increasing aeration rate appeared again. The loss of performance can be seen in Fig. 13.

Germain et al. [12], studying the aeration effect depending on flux variations, found a transitional flux between 16.5 and $22 \text{ L m}^{-2} \text{ h}^{-1}$. Below this value no significant fouling was observed whereas, above it, high aeration velocities were required to maintain low fouling rates. This would imply that air sparging is more efficient in operating conditions that are unfavourable towards fouling (high filtration flux, high suspended solids (SS) concentration). Gui et al. [13] tested aeration with SS concentrations of 10 g L^{-1} and of 1 g L^{-1} . Its effect was seen only for the highest concentration. Similarly, Lu et al. [52] only saw the effect of bubbling parameters when the yeast concentration of their filtrated solution increased from 3 g L^{-1} to 5 g L^{-1} .

Finally, it must be noted that some studies report a negative effect of aeration. In SMBRs filtrating synthetic wastewater, strong aeration (800 L h^{-1} , SAD_m of $8 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$) resulted in floc breakage and promoted the release of colloids and solutes [62]. This negative impact of aeration on mixed liquor was studied in other works and is discussed in Sections 3.3.2 and 3.3.3. In a tight hollow fibre module filtrating a baker's yeast suspension, Martinelli et al. [63] showed that local airflow rate increased the fouling resistance and thus reduced the performance of the SMBR. This is explained by the fact that the horizontal liquid flow induced by the bubbles increased with airflow rate and made it probable that particles would reach the filtration layer and contribute to higher fouling. However for this last study, it should be noted that the SS concentration was lower than in the previous works. It was only 0.56 g L^{-1} whereas it was mainly around 10 g L^{-1} in previously quoted works.

Table 2
Effect of air sparging and operating conditions on filtration performance.

Reactor volume (L)	Membrane surface area (m ²)		J (L m ⁻² h ⁻¹)	MLSS (g L ⁻¹)	U_g (m ³ m ⁻² s ⁻¹)	SAD_m (m ³ m ⁻² h ⁻¹)	Observations	Refs.
21,400	HF	88	7.9–15.4	8–12	0.0068–0.0102	0.20–0.75	Cake removing efficiency was affected by the standard deviation of the flow velocity. Increase in airflow rate enhanced the cake removal but there was a critical value beyond which it no longer had any effect.	[58]
3.5	FS	0.106	10–28	6.8–16.5	0.018–0.23		Membrane fouling increased exponentially with increase in J and with decrease in U_g . Fouling was controlled even at high J by adapting U_g .	[38]
93.5	HF	4	3–10	1–10	0.0062–0.043		J was the key factor. Aeration was more effective at high SS concentration. Correlation found between fouling, critical flux, airflow rate and SS.	[13]
9	FS	0.1	16.9	8–10	0.005–0.025		An increase of aeration intensity led to a plateau region of crossflow velocity (0.69 m s ⁻¹ for U_g of 0.017 m s ⁻¹)	[60]
12,700	HF	42	5.5–33	4.3–13.5	0.07–0.13		Permeate flux had the greatest influence on fouling rate whereas membrane aeration had the least effect. Existence of a transitional flux between 16.5 and 22 L m ⁻² h ⁻¹ , above which strong aeration was required to maintain low fouling.	[12]
12	HF	0.1	6–60 Constant P 3.97 kPa	6		1.5–8	Low aeration could not remove the foulants whereas high aeration induced severe floc breakage due to stronger shear. The smaller size of particles was related to dramatic fouling increase.	[62]
950	HF	66.9–69.7	24–44	8–12		0.12–0.46	Exponential decrease of the fouling ratios with increasing scouring aeration intensity. Independence of the effect of scouring aeration intensity and permeate flux on fouling ratios.	[64]
90	HF	0.032	50	0.56		0.26–3.12	Low shear induced by air injection (0.25 Pa). Local airflow rate is the key factor. Horizontal liquid flow due to air injection increases the particle transport towards the membrane and leads to fouling.	[63]

Abbreviations: HF, hollow fibre; FS, flat sheet.

Some values of this table were calculated from other values extrapolated from graphics or reported from these graphics and may consequently not be totally accurate.

The fact that aeration is more efficient when operating conditions yield heavy fouling is confirmed. However the influence of airflow on fouling is complex regarding the involved phenomena which will be described in Section 3.

2.4. Bubbling

Table 3 sums up the effect of bubbling. It should be noticed that most of the results presented were obtained with synthetic effluent which could modify the fouling mechanisms because of various parameters such as the form in which the model substances were obtained, the chemical nature of the effluent, the absence of a solid matrix in these models, the influence of pH or ions on the model polymer's aggregate and the change in properties (aggregate size or concentration) during the course of the experiments [8].

As advised in recent years, the bubbling parameters should be investigated in large detail. Krishna et al. [65] found three to six times greater velocities in a bubble swarm than for an isolated bubble. Larger bubbles generated strong turbulences in their wake and following bubbles were accelerated. Providing larger bubbles

would enhance the turbulence and increasing the frequency would improve the effect of bubbles on each other and lead to more homogeneous fouling. But this costs energy. Number density ρ is expressed as the number of bubbles (N_b) over the airflow rate [53]:

$$\rho = \frac{N_b}{Q_g} = \frac{1}{V_b} \quad (6)$$

where V_b is the bubble volume and Q_g is the airflow rate. This density is proportional to (bubble radius)⁻³ and it appears that halving the bubble size provides 8 times as many bubbles for the same airflow rate. This can also be written as

$$Q_g = fV_b \quad (7)$$

where [66] the bubbling frequency f is directly related to a number of bubbles. These equations show the relation of bubble size and frequency with the airflow, which is linked to energy consumption. The bubble size and frequency must be optimized to provide the best hydrodynamic conditions but, at the same time, lower the energy necessary to introduce them.

Table 3
Influence of bubbling parameters on filtration performance.

Bubble size (mL) Nozzle size (mm)	Solid type MLSS (g L ⁻¹) Mean diameter (μm)	Membrane surface area (m ²)	SAD _m (m ³ m ⁻² h ⁻¹)	Observations	Refs.
– 0.5–2 mm	Sludge 8–10 g L ⁻¹	FS 0.1	Aeration intensity 0.005–0.025	Optimal value related to higher crossflow velocity: it first increases with aeration intensity and then reaches a plateau. Smaller bubbles lead to higher values of crossflow velocity and better control of fouling due to a more uniform distribution of air.	[60]
0.09–8.36 mL –	Bentonite 1 g L ⁻¹ 5 μm	HF 0.011	0.014–2.74	Larger bubbles at high frequency provide the biggest standard deviation of liquid velocity and smallest standard deviation of fluxes between fibres. However, the smallest bubbles at high frequency would be more profitable regarding energy consumption.	[23]
5–200 mL –	Electrolytic solution – –	FS 0.3	0.004–1	Dependency of mass transfer coefficients on bubble size and frequency had two regions: first increasing and then reaching a plateau region ≥ optimal size and frequency: 60 mL and 0.4 Hz.	[71]
0.11–55 mL – –	Bakers yeast 0.56 g L ⁻¹ 5 μm	HF 0.032	0.93–3.125	Rather low shear induced by air injection (<0.25 Pa) Horizontal flow leads to fouling, related to higher airflow rate. No bubble characteristic influence	[63]

Abbreviations: HF, hollow fibre; FS, flat sheet.

Some values of this table were calculated from other values extrapolated from graphics or reported from this graphics and may consequently not be totally accurate.

2.4.1. Size of nozzle and bubbles

In tubular membranes, slug flow has been widely studied for the enhancement of filtration performance and turns out to be favourable [11,66–68]. It is more complex in SMBRs where most of the time flow is unconfined and slug is not necessarily the most suitable kind of flow to save energy.

The nozzle size influences the kind of bubble and its effect has been studied. In a flat sheet MBR fed with raw domestic sewage, Sofia et al. [60] better controlled fouling with a 0.5 mm diffuser instead of a 2.0 mm one. Small bubbles induced higher crossflow velocities and a stronger shearing effect than coarse bubbles (0.69 m s⁻¹ against 0.4 m s⁻¹). They were able to operate their MBR for 8 months whereas the maximal TMP value that they set was reached in 4 weeks using coarse bubbles at the same aeration intensity (0.017 m s⁻¹). The finer and more uniformly distributed bubbles were thought to make more stable operation possible with lower TMP across the membrane. Fane et al. [69] found similar results with hollow fibres filtrating bakers yeast. A nozzle diameter of 0.5 mm was more efficient than a diameter of 1.0 mm in controlling fouling characterized by TMP variations. The authors deduced that the more numerous shear events provided by smaller bubbles were related to the better fouling control. This was confirmed in other studies dealing with hollow fibres, many small bubbles being more efficient than few large bubbles at the same airflow rate [23,53,70].

The effect of bubble size can vary [23]: small bubbles gave the same fouling behaviour (related to standard deviations of liquid velocities and consequently turbulences) as big bubbles that needed ten times their airflow rate. Although the biggest bubbles involved smaller standard deviations of individual fibre fluxes, the author concluded that small bubbles were better regarding their energy consumption. This would mean that turbulence is a more important mechanism than flux homogeneity.

A larger nozzle provides larger bubbles but with lower frequency at the same airflow rate [52]. Three nozzle sizes were tested: 1, 3 and 12 mm. At low yeast concentration (3 g L⁻¹), each nozzle had the same effect on fouling tendency. Results were different for a higher yeast concentration (5 g L⁻¹). At low airflow (80 mL min⁻¹ or SAD_m of 0.25 m³ m⁻² h⁻¹), large air bubbles and slug flow were more efficient than small bubbles generated by smaller nozzles. This was related to the stronger wakes of larger bubbles. However, when airflow increased, nozzle size had less influence and, when 150 mL min⁻¹ was reached, it had no effect.

Similar results were found in another study that was conducted using a flat-sheet module which filtered water [71]. Setting a rather low aeration frequency (0.067 Hz) enabled bubbles to be separated and prevented them from influencing each other. An optimum bubble size of 60 mL was found to improve the mass transfer estimated by an electrochemical method. It corresponded to a slug flow. Above this volume, no improvement was observed. This could be related to the wake size of bubbles. It had already been observed by Campos and Guedes de Carvalho [72] that there was a critical length for slugs beyond which further increase had no effect on the wake size.

2.4.2. Frequency

Increasing bubble size and frequency led to better fouling control [23]. However it induced higher operational costs and these parameters could be improved regarding energy savings. For volume ratios of small:medium:large bubbles of 1:12.5:93, corresponding to bubble sizes of 0.09, 1.13 and 8.36 cm³, small bubbles were more effective at high frequency. A frequency of 2 Hz for medium bubbles generated the same standard deviation of liquid velocity (related to fouling control) as large bubbles at a frequency of 1 Hz, but using only 30% of the air required for large bubbles. The result was the same between small- and medium-sized bubbles for respective frequencies of 2 and 0.5 Hz (Fig. 14).

The effect of bubbling frequency on shear rate has also been assessed [57]. Different frequencies were tested for small, cap and

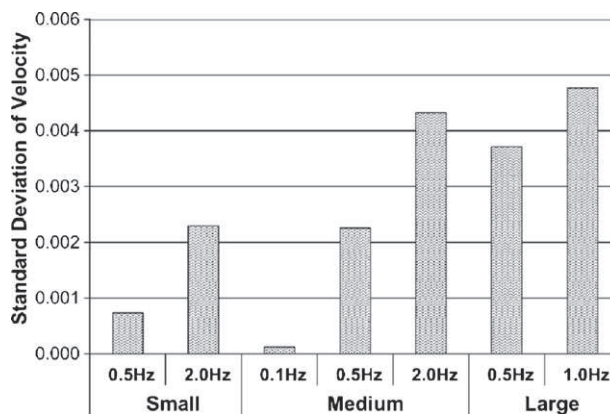


Fig. 14. Effect of bubbling frequency on standard deviation of velocity [23].

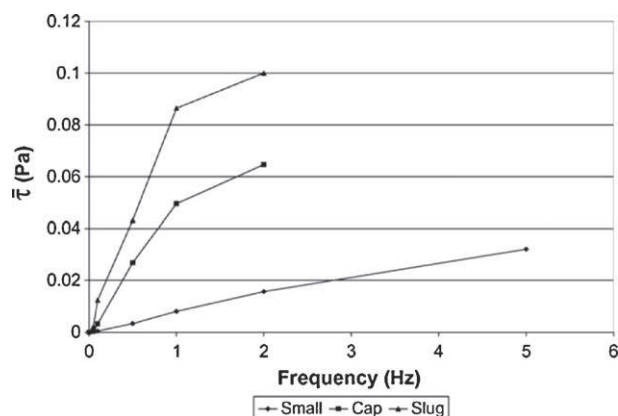


Fig. 15. Influence of bubbling frequency on mean shear stress at membrane surface [57].

slug bubbles. Their influence on shear stress when no axial flow was imposed is presented in Fig. 15. Similar trends were observed for the standard deviation of shear stresses. It can be seen that a plateau was reached for each kind of bubble. This study focused on the influence of shear stress on fouling (see Section 3.3). Here, it was related to fouling control efficiency with the observation of TMP increase rates (Fig. 16). It can be seen that increasing the frequency by more than 1 Hz does not decrease fouling rates much. This confirms the existence of a threshold value and the need to optimize airflow rate.

In this study, the same airflow rate provided 400 small bubbles for one slug. Without axial flow, a TMP increase rate of 2 kPa min^{-1} was found for airflow rates of 0.01 L min^{-1} using small bubbles and of 0.1 L min^{-1} using cap or slug bubbles. The authors suggested that two mechanisms could account for the effect of bubbles on submerged hollow fibres: contact between bubble and fibres but also bubble wakes. For small bubbles, few contacts with fibres were observed compared to bigger ones. As similar performance was obtained for small bubbles with tenfold lower airflow rate, the authors deduced that bubble wakes were the predominant mechanism that determined submerged hollow fibre performance.

Similarly, an optimal frequency of 0.4 Hz has been reported in a flat sheet module [71]. Beyond this value, the energy costs associated with increased frequency are no longer acceptable. These studies confirm that an optimal airflow exists.

2.5. Sequencing of aeration

Intermittent aeration on each side of a submerged hollow fibre cassette has been reported as an interesting improvement over

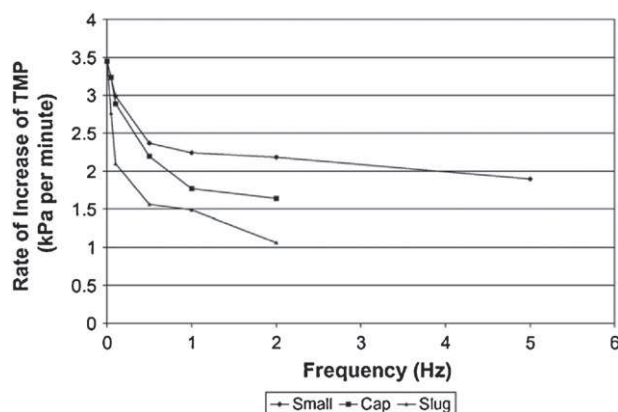


Fig. 16. Influence of bubbling frequency on rate of increase of TMP [57].

continuous aeration [73]. Similar conclusions have been reported by Van Kaam et al. [74] for a submerged hollow fibre bundle. The relation between relaxation time after high shear stress and floc size would be a factor limiting fouling. Rheological measurements showed that activated sludge stability evolved with shear stress and was used to simulate the effect of hydrodynamics on biological media [75]. This demonstrated the benefit of intermittent aeration. It prevented fouling and floc damage while minimizing energy costs.

The effect of air injection was greater in the absence of TMP [35]. A judicious combination of aeration sequences with those of filtration/relaxation seems essential for a proper management of fouling. To save energy, cutting off the aeration for half the time was tested [76]. The SMBR was run with a sequence of 10 min of filtration at $35 \text{ L m}^{-2} \text{ h}^{-1}$ followed by 30 s of backwash. Airflow rates from 0 to 4 L min^{-1} (SAD from 0 to $24 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$) were tested. Sequences of continuous aeration were compared with sequences with aeration 10 s on/10 s off at the same airflow rate. The fouling rates were similar, meaning that 50% of the energy could be saved. In a new geometry module, aeration demand was reduced to $260 \text{ NL m}^{-2} \text{ h}^{-1}$ owing to sequencing [77]. Moreover, low aeration during filtration and high aeration during backwash reduced aeration demand to $190 \text{ NL m}^{-2} \text{ h}^{-1}$, which is much lower than in the conventional MBR processes.

But a recent study pointed out contrary results [70]. Intermittent aeration was found to be less effective than continuous aeration in a hollow fibre SMBR. Aeration was set 1 min on/9 min off. Air was provided when filtration was stopped (filtration sequence of 9 min on/1 min off). Sequences were run for SAD_m from 10 to $75 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$ (to be compared with continuous aeration mode with SAD_m of $1\text{--}7.5 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$). This result could be explained by the fact that rather high SAD_m were set during intermittent filtration and this could have had an impact on the biological media.

2.6. Conclusion on global effect of aeration

The global effects of aeration have been investigated in this section. Aeration is more efficient when running conditions yield heavy fouling (i.e. high MLSS concentrations, high filtration flux, etc.). Among the numerous parameters involved, a trend is emerging as the existence of a threshold of filtration efficiency linked to the gas flow rate. But given the wide range of SMBRs configuration and of operational parameters (that are interrelated) it is not possible to set an "optimal" airflow rate.

Inside SMBRs gas flow is most of the time unconfined. Thus generating homogeneous hydrodynamic conditions with slug flow is difficult. Slugs or huge bubbles would provide stronger wakes but cost more energy. They were efficient when the flow was confined: in hollow fibres surrounded by a cylindrical pipe [52] as well as in a flat sheet module [71]. On the other hand, smaller bubbles generate more homogeneous turbulence in unconfined flow. Many small bubbles homogenize the shear effect of air sparging and prevent the creation of dead zones while limiting the energy consumption.

Some other "secondary" parameters confirmed the existence of a threshold, such as size and velocity of bubbles. At a more local scale this threshold value could be linked to parameter such as standard deviation of flow [58]. The complexity of the analysis leads some researchers to the use of modelling to contribute to the phenomenon description and mastering. In this context, investigations at the local scale appear to be of prime importance.

3. Local phenomena induced by the aeration

Several phenomena induced by aeration at local scale turned out to have an impact on fouling: movement of fibres, turbulence and the associated back-transport, shear stresses at the membrane

surface and, finally, shear stresses in the mixed liquor which influence floc size and EPS release. However, up to now, none of these phenomena have been found to be the key factor for the impact of aeration on the limitation of fouling. Since the impact of each of these phenomena may depend on the operating conditions, the actual step from the hydrodynamics point of view consists of quantifying the impact of each of the operating parameters on them. A first option may be to model each of these phenomena independently and then to group the models or to compare the results of the models in order to find the range of impact of each phenomenon.

3.1. Turbulence and back-transport

Turbulences have widely been reported as having a beneficial effect in membrane processes. It is always desirable to suppress concentration polarization by promoting turbulence or running at lower fluxes [78]. Moreover, turbulence enhances the back-transport of particles. Spacers promoting turbulence are also used in many applications.

In a SMBR, the cake removing efficiency of the airflow was affected by the standard deviation of the flow velocity [58] which is related to its turbulence. Standard deviation of flow velocity variations agreed with those of TMP. An optimal value was found for the airflow rate, linked to the fact that standard deviations of flow velocity no longer increased beyond this value.

More recently, Orantes et al. [79] managed to improve performance of their MBRs by doubling the airflow rate. Aeration was placed below each submerged module and designed to create turbulence around the modules. Switching the airflow from 25 to 50 Lh⁻¹ enabled the rate of change of TMP to be decreased. In consequence the MBR could have been run with cycles lasting over 200 days without a change in permeation flux and with no intermediate washing instead of cycles between 10 and 50 days. The authors relate this improvement to the local turbulences created by the airflow in the vicinity of the hollow-fibre module (another hypothesis for the beneficial effect of aeration is the local intensification of oxygen transfer).

A study confirmed the importance of turbulence for filtration performance. The increase in the standard deviation of liquid velocities induced by air has been shown to be more effective in MBR filtration than the increase of the average velocities [23]. The beneficial effect of aeration was estimated with the final TMP after a given time of filtration at constant flux. From Fig. 17, no clear relation appears between average liquid velocity and final TMP, whereas increasing standard deviation improved the filtration performance (Fig. 18) by lowering the final TMP. Thus generating unsteady state flows with large standard deviation in local velocity could be a strategy to improve MBR performance.

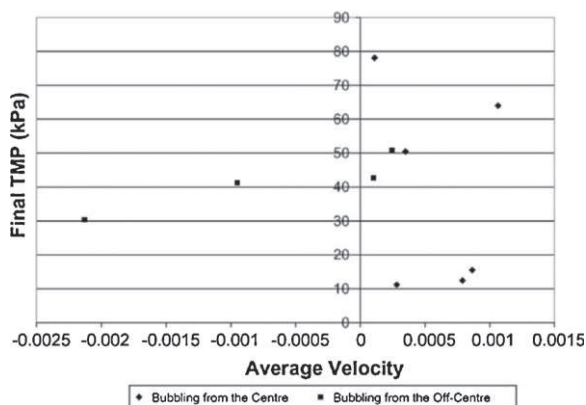


Fig. 17. Effect of average liquid velocity on TMP variations [23].

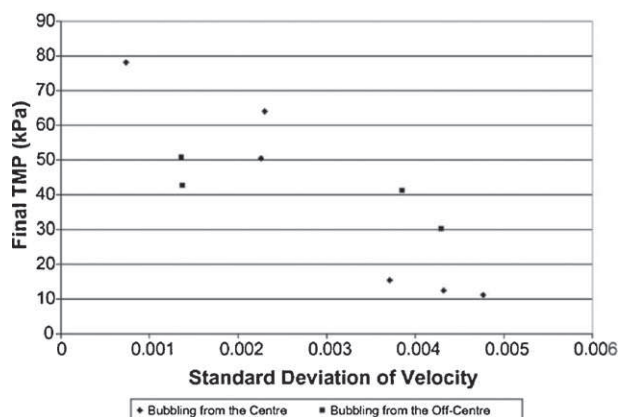


Fig. 18. Effect of standard deviation of liquid velocity on TMP variations [23].

3.2. Fibre movement: amplitude and effect of looseness

Besides influencing the back-transport of the particles, turbulences shake the fibres and make them move, which is beneficial for filtration or for fouling prevention [42,58].

TMP has been observed to rise 40% faster for tight fibres than for loose ones [53]. Tightness was 96%, i.e. the distance between the potted extremities was equal to 96% of the fibre length. The benefit of loose fibres has already been reported elsewhere [80]. Observation of the tight bundle showed that many particles adhered to the fibres, particularly in the centre of the bundle. When the hydrodynamic environment is more restrictive (high SS concentration, low aeration rate) the filtration performance of the module is greatly diminished. Since inter-fibre fouling is difficult to control by back-washing or by chemical cleaning, the problem may be greater for real scale plants with larger modules and longer use.

However, although loose fibres are preferable to limit fouling, it is important to keep the tension within a given range to prevent them from breaking. Furthermore, an optimal tightness (99%) was found with different aeration conditions [57]. A compromise should be found between tight fibres, which damp the bubbling effect, and loose fibres, which can move away from the influence of the bubbles. In the same study, fibre displacement was investigated. To observe the fibres, fluorescent particles were fixed at their mid-height. The velocity of the fibres, which was calculated from their displacement versus time, did not show any effect on the rate of increase of TMP whereas fibre acceleration, which was determined from the rate of change of fibre velocity, improved it.

A different interpretation has been given by Bérubé and Lei [81]. Promoting lateral sway in a multi-fibre module could lead to physical contact between membrane surfaces and enhance the permeate flux by mechanical erosion of the cake layer. Pseudo steady-state permeate flux has been found to be 40% higher in a multi-fibre module than for a single fibre.

Another mechanism has been proposed to account for the better performance of loose fibres [82]: the flow paths of bubbles rising in this configuration are not confined to a specific region, as is the case for tight fibres. In consequence, a larger number of fibres could benefit from the sparged bubbles.

Given the importance of fibre movement the influence of their dimension has been studied. It was found that fibres with a large diameter are more prone to fouling while smaller fibres would have a greater response to the surrounding hydrodynamic environment [42]. It was confirmed in a later study [53]. This tendency is linked to the smaller displacement amplitude of large fibres (Fig. 19). However, pressure losses are higher in smaller fibres and a balance must be found. The problem is the same with fibre length: when the length increases, the amplitude also increases and fouling is lower,

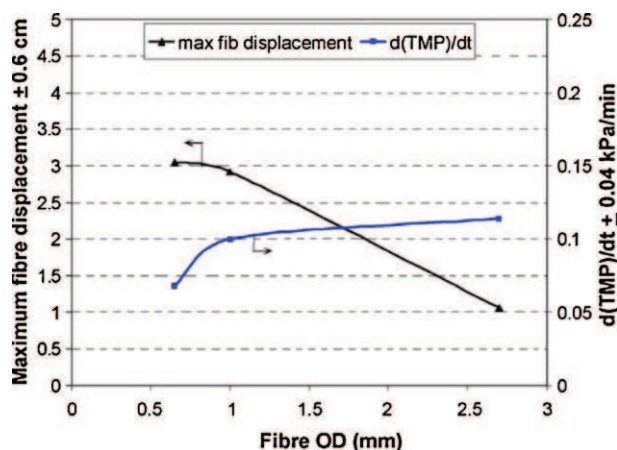


Fig. 19. Effect of diameter on fibre movement and TMP variations [53].

but pressure losses also increase, thus reducing available TMP. For instance, Fane et al. [69] improved the performance of their MBR by increasing the fibre length (from 50 to 70 cm), although this caused a faster initial rise in TMP.

Mechanical displacement of a single hollow fibre has also been tested [53]. The fibre was moved laterally with an amplitude of 3.8 cm every 2 s. This resulted in fouling being reduced to a third of the value found for a stationary fibre without bubbling but it remained less efficient than aeration. The results are presented in Fig. 20. Curve (A) corresponds to mechanical movement without bubbling and (B) to suction only. It appears that TMP variations are more reduced with the use of bubbling (C).

Mechanical movement of fibres could become effective at higher frequencies [83]. Axial vibration in a 10 Hz frequency range enabled industrially relevant operating fluxes to be reached with critical fluxes of $60\text{--}80\text{ L m}^{-2}\text{ h}^{-1}$. Addition of transverse vibration resulted in the critical flux being practically doubled ($130\text{ L m}^{-2}\text{ h}^{-1}$ at 10 Hz).

3.3. Aeration shear stress

Shear stresses induced by aeration influence membrane fouling by two mechanisms: they can have a beneficial effect with the enhancement of filtration performance due to scouring of the membrane surface but they can also have an impact on biological floc characteristics. To our best knowledge few studies dealt with this last point. Indeed tackling this issue is made difficult by the lack of standard method for sludge characterization. Activated

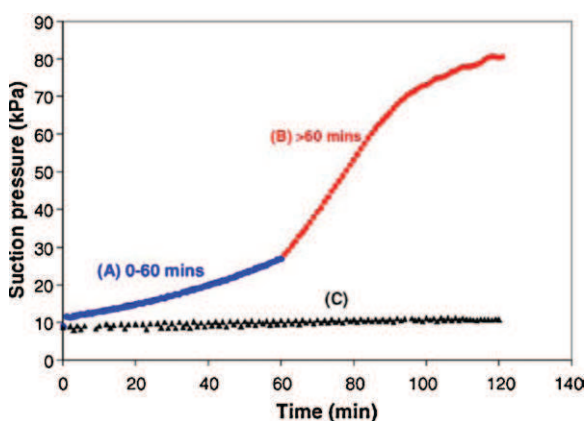


Fig. 20. Comparison of mechanical displacement and aeration effect on TMP variations [53].

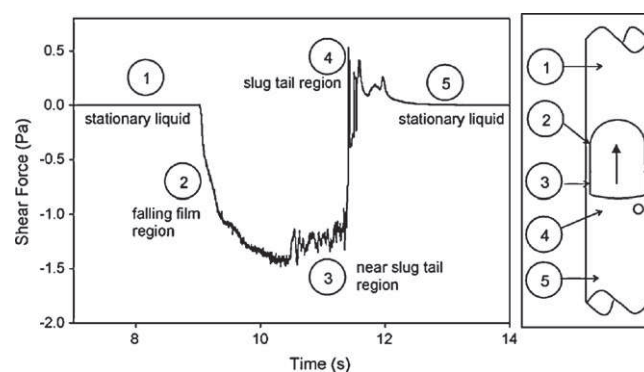


Fig. 21. Wall shear stress distribution around a gas slug rising in stationary liquid in a vertical pipe, as measured experimentally using the electrochemical shear method [89].

sludge is described as a non-Newtonian fluid [84,85] composed of three main fractions: solutes, colloids and particles [1]. There is no standard method to separate those [6] and it is consequently not obvious to compare the mentioned studies. Nonetheless further work is required to quantify the beneficial influence of aeration through membrane scouring and the potential negative impact on mixed liquor through changes of biological parameters such as floc size (and activated sludge fractionation) and also EPS concentrations.

3.3.1. Shear stress on membrane surface

To evaluate shear stress on membrane surfaces, the electrochemical shear method has been widely used [82,86–88]. An example of shear measurement with this method is shown for a gas slug in Fig. 21.

Both the time-averaged value and the amplitude of wall shear stress influenced flux enhancement but its frequency had no effect in a flat sheet module [86]. In another study, the fluctuating component of wall shear rate appeared to be the quantity that controlled the transfer processes at the wall of the membrane [87].

A further work described the importance of the two parameters in the tight hollow fibre configuration [57]. At low values of average shear stress, the performances of hollow fibres were dominated by the standard deviation of the stress. As the mean value of shear stress increased (with increase of the axial flow), standard deviation of shear stress decreased and the mean value became the predominant factor regarding fouling reduction. In this study shear stresses were determined from the velocity vectors evaluated by PIV.

Shear stresses in a simulated module of hollow fibres were experimentally examined with the electrochemical shear method for monophasic and biphasic flows [88]. The 'active' hollow membrane fibres were replaced by Teflon tubes of similar diameter (i.e. 2 mm). The electrochemical shear probe was mounted flush with the surface of the Teflon tube. The average shear stresses and their variations were much greater with aeration (Fig. 22).

The study also showed that they were not distributed evenly along the length of fibre. For biphasic flow, greater stress was found in the upper part of fibres. In consequence, the authors suggested that aspirating permeate from the top would be better. It would generate greater permeation fluxes where the shear related to aeration was the strongest, and thus homogenize fouling. They also advised the use of long fibres. However, a compromise had to be found with the pressure losses due to the increased length. Tight and loose configurations were also tested. It was proposed that close proximity of other fibres in a tightly configured multi-fibre module could potentially shield certain areas of a fibre from both the bulk liquid flow and the sparged gas bubbles. As a result, the average shear force generated over the entire length of a fibre sur-

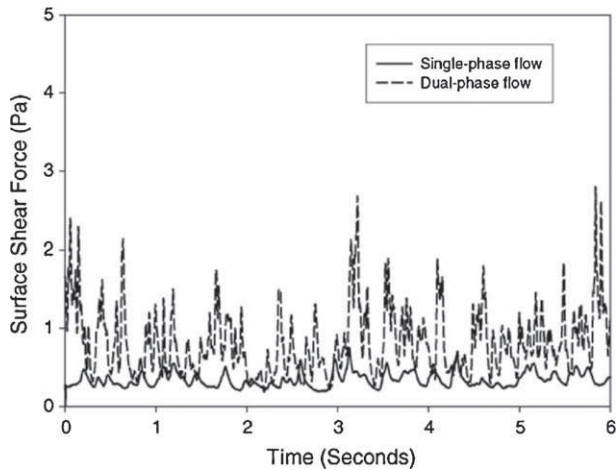


Fig. 22. Shear force on simulated hollow fibre surface for single and dual-phase flows [88].

face would be lower for tightly configured multi-fibre modules, which could explain the benefit of a loose configuration.

But different results were found in a further study [82]. Unlike the case of a tight configuration, no negative shear was observed for loose fibres, which means that gas sparging did not induce flow reversal. Consequently the scouring of the fibre by falling film, an important mechanism in confined systems [11] did not occur. Moreover, contrary to what was expected, the average shear signals were, in general, lower than that observed in tight configuration, apart from some occasional peaks. Considering this result, the authors suggested that the fact that loose fibres move, and consequently have more probability of benefiting from air sparging, could explain their better performance. This would imply that aeration homogeneity is a predominant mechanism for filtration. The shear profile surrounding the fibre was also assessed by rotating the shear probe. When the probe faced away from the rising bubbles (probe was rotated 180° relative to the air diffuser) shear profiles were similar but lower in magnitude compared to those found when the probe faced the air diffuser. This result may be a first step in quantifying the degree of foulant control of fibres at different locations in a full-scale submerged hollow fibre system where there may be a great difference between the shear forces applied to the outer fibres, closer to air diffusers, and fibres located inside the module. This kind of probe could be used for a more accurate investigation of the homogeneity of air distribution through shear distribution in hollow fibre bundles and could thus lead to improvements in the air sparging efficiency.

Shear intensity can be directly linked to airflow rate through aeration intensity. Several models [59,90,91] use the apparent shear intensity G defined as

$$G = \left(\frac{\rho_s g U_g}{\mu_a} \right)^{1/2} \quad (8)$$

where ρ_s is the sludge density, g is the constant of gravity, U_g is the aeration intensity and μ_a is the apparent viscosity. This expression was deduced from an energy analysis where power dissipation was expressed as a function of shear stress and velocity gradient.

CFD simulations were used to provide order of magnitude of shear stresses. Ndinisa et al. [92] and Prieske et al. [93] calculated shear stresses in the flat sheet configuration. They respectively found maximum value of 0.7 and around 4 Pa. More recently, attempts have been made to model hollow fibres but unconfined flow is very difficult to model and the effect of bubbles in submerged hollow fibres is still being assessed. For instance, in 2006 Bérubé et al. [88] stated that CFD analysis of dual-phase flow at the

level of resolution of the motion and interaction of bubbles in non-confined three-dimensional systems was complex and beyond the scope of their study. Consequently they only treated the monophasic case and had problems even with this model. CFD simulations provided higher shear forces than those found experimentally. For a crossflow velocity of 0.2 m s^{-1} , average shear forces of 0.3, 0.26 and 0.24 Pa were predicted by CFD whereas the experiment gave 0.25, 0.18 and 0.15 Pa for respective heights of 10, 26 and 32 cm on 42-cm-long fibres. The fact that the fibre was modelled as a rigid body was thought to be the cause of this difference. This highlights the difficulty of modelling hollow fibres SMBRs. However this kind of investigations at a local scale is necessary to deepen the understanding of the mechanisms involved and the way that bubbles impact on filtration performance. In a recent study a particular configuration of SMBR was used to do so [63]. The module was composed of only 6 tight fibres to eliminate fibre movement and make it easier to simulate the geometry accurately. Wall shear stresses were calculated along the membrane surface and rather low values were found with a maximum of 0.25 Pa.

3.3.2. Shear stress effect on sludge fractions

Particle size distribution (PSD) was found to be one of the main parameters influencing membrane fouling in an SMBR [94]. It should be noted that a small correlation was found between PSD and EPS concentrations, which effect will be discussed in the next part. The authors suggested that PSD should be taken as a separate membrane fouling factor. A later study focused more precisely on the effect of particle size. Mixed liquor with mean floc diameter larger than $80 \mu\text{m}$ was found to have good filterability (with a lower increase rate of membrane resistance) whereas, when the mean floc diameter was smaller than $80 \mu\text{m}$, floc size had a more marked effect on filterability [95]. Although no general trend can be deduced from these works (the critical particle size found in these studies may depend strongly on the system configuration and the membrane used), they highlight the importance of understanding the effect of shear on floc size to run MBRs more efficiently.

The direct effect of aeration on sludge fractionation was assessed in a hollow fibre SMBR [76]. Airflow rate ranged from 0 to 4 L min^{-1} and mean velocity gradients were estimated from 0 to 337 s^{-1} . Low aeration led to stronger fouling when the SS content increased from 7.0 g L^{-1} to 14.3 g L^{-1} and 21.0 g L^{-1} due to the deposition of MLSS in the membrane. This was observed for aeration rates below 2 L min^{-1} , corresponding to a SAD_m of $12 \text{ m}^3 \text{ m}^{-2} \text{ h}^{-1}$. Above this value, increasing the aeration did not have any beneficial effect. The fouling rate was the same for the three SS concentrations studied because the solutes and colloids became responsible for fouling. The influence of the different fractions is presented for the tested airflow rate in Fig. 23. For low airflow rates, MLSS was the major

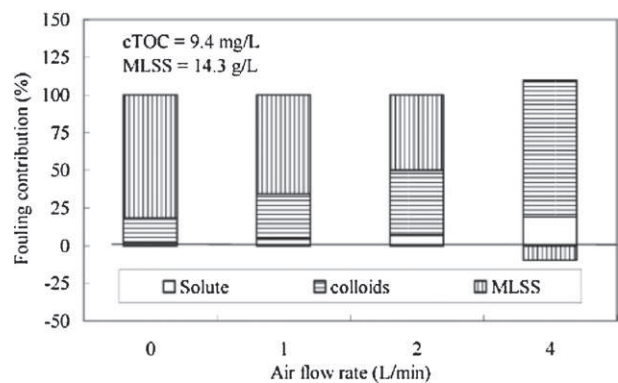


Fig. 23. Contribution of the activated sludge fractions to fouling depending on the airflow rate [76].

foulant; shear was not strong enough to remove the cake layer and prevent the deposit of MLSS in the membrane. This explained why fouling rates were higher for high MLSS concentrations. When aeration intensity increased, colloids became the major foulant and MLSS made a negative contribution to fouling: they acted as a secondary membrane that prevented pore blocking as well as adsorption of colloids and solute on the membrane surface.

Similar results were found later [62]. Three SMBRs were run with different airflow rates: 150, 400 and 800 L h⁻¹ (SAD_m of 1.5, 4 and 8 m³ m⁻² h⁻¹, respectively). At the beginning of the run (first 4 h) aeration had a positive effect. It removed foulants from the membrane surface and the MBR, with the highest airflow rate leading to the highest permeate flux. But in the long term (up to 400 h) only the MBR with medium airflow rate showed a steady permeate flux value. This was explained by the formation of a fouling layer acting as a second “dynamic membrane”. For the low airflow rate MBR, severe fouling occurred due to the formation of a cake layer that could not be removed by air sparging whereas, for the high airflow rate MBR, too high an aeration intensity led to the release of EPS and the breakage of sludge flocs. PSD analysis gave an insight into these mechanisms. It showed that, in the 3 MBRs, 70% of the particles had sizes ranging from 10 to 100 μm. However, only 20% were smaller than 50 μm in the low airflow MBR whereas 48% were below this size in the high airflow one. Moreover, the percentages of particles smaller than 10 μm were 0.126, 0.226 and 0.826 in the low, medium and high airflow rate MBRs respectively. This emphasizes the importance of these small particles, which is discussed hereafter.

3.3.3. Shear stress effect on extracellular polymeric substances

Besides having influence on fouling through a physical mechanism that modifies sludge fractionation, shear stresses can also impact the behaviour of biological media. Rochex et al. [96] applied shears from 0.055 to 0.27 Pa on biofilms in a conical Couette-Taylor reactor. High shear decreased the biofilm diversity and slowed down biofilm maturation. In the case of SMBRs, it is of interest to investigate how shear stresses modify the EPS concentrations. EPS are substances secreted by bacteria, which enable them to form aggregates such as flocs or biofilms. They may act on MBR fouling (i) because of their influence on flocculating ability and (ii) because of the formation of biofilms on the membrane surface. The death of bacteria in this biofilm (lower layer of cake) and the resulting release of EPS could be involved in the TMP jump [19]. More recently, quorum sensing, the communication among bacteria via a small signal molecule, has been introduced as a new biofouling paradigm in MBRs for wastewater treatment [97]. Biofouling was prevented by regulating the soluble EPS concentration through quorum sensing control. Given their importance for MBR performances, EPS influence on the process has already been reviewed [6–8,98].

Park et al. [99] found that, in an airlift MBR, greater recirculation velocity induced more severe turbulence and reduced fouling until a threshold value was reached. But too high a recirculation velocity had a significant negative effect on the behaviour of flocs. It reduced their size and led to a release of polymeric substances, causing a rapid loss in membrane permeability.

Menniti et al. [100] studied the impact of shear rate on EPS production in a stirred SMBR. In the short term, high shear (1840 s⁻¹) was applied to activated sludge for 6 h. It resulted in a release of SMP detected through the increase in protein concentration, the carbohydrate concentration remaining little affected. Thus the authors observed an increase in fouling with a strong contribution of the soluble fraction of the mixed liquor. Increased mechanical shear was thought to erode the floc-associated EPS. Opposite effects were observed in a long-term experiment (134 days). Higher shear (1124 s⁻¹ against 160 s⁻¹) reduced the concentration of bound and

soluble EPS. This was correlated with lower fouling. For the second long-term experiment (56 days), fouling potential was still lower in the high-shear reactor. Floc-associated EPS were studied with atomic force microscopy to evaluate their adhesion force and stickiness. EPS compounds subjected to higher shear showed stronger adhesion. Bio-physical adaptation of micro-organisms to the heavy mechanical stresses imposed by shear could explain this behaviour. These experiments dealt only with mechanical shear. Although they provide interesting results, EPS release specifically due to aeration should also be assessed. To the best of our knowledge, little work has so far been done on this subject in the SMBR configuration.

Ji and Zhou [101] observed the following effects of increasing aeration on EPS in the long term: increased concentration and decreased protein/carbohydrate ratio for soluble EPS (SMP) and both lower concentration and lower protein/carbohydrate ratio for bound EPS. The experiments were carried out with three lab-scale hollow-fibre SMBRs with aeration rates of 120, 80 and 40 L h⁻¹, which corresponded to respective SAD_m of 0.8, 0.53 and 0.27 m³ m⁻² h⁻¹. Filtration was performed on synthetic wastewater with a flow of 8 L m⁻² h⁻¹ for 170 days. Filtration cycles were defined as the period between two successive physical cleanings, the membrane being removed for cleaning it as soon as TMP reached 50 cmHg. The authors defined the parameter V_f that corresponded to the final VSS mass on the membrane at the end of each cycle (g m⁻²). The strongest correlation with the TMP was found for the product of the protein/carbohydrate ratio by V_f . This means that the composition and also the quantity of sludge that has accumulated on the membrane have an impact on fouling. The beneficial effect of aeration is explained by the declining protein/carbohydrate ratio. This is consistent with another study which showed that activated sludge flocs with higher protein/carbohydrate ratios were less stable [102]. Hence it was possible to reach larger values of V_f , thus accumulating more material on the same membrane for the same fouling, and consequently work on longer cycles. In this case [101], aeration had a combined impact, by scouring the membrane and modifying the EPS composition. It appears that, under higher airflow rate (and consequently shear stress) the microbial community reacts differently. It seems to adapt towards a more stable floc structure with a lower protein/carbohydrate ratio.

A new mechanism has been proposed to account for the beneficial effect of aeration related to its influence on predation [103]. Predation by the large aquatic earthworm *Aelosoma hemprichi* increased the floc-associated EPS production in MBR biomass. In this study, the aeration did not have a direct effect on EPS concentrations but *A. hemprichi* proliferated in low-shear experiments whereas they were never observed in higher-shear reactors. Membrane fouling was related to the EPS concentrations, which showed the importance of predation in MBR fouling management.

3.4. Conclusion on local phenomena induced by the aeration

In MBR the filtration flux infers a transport of solids and soluble elements towards the membranes which contributes to fouling. Coarse bubble aeration is imposed to limit this fouling. There are several hypotheses of local phenomena involved in the effect of this aeration, without knowing how to quantify their respective contribution:

- The movement of bubbles infers a movement in the inverse direction of the filtration of the fluid and of the solid close to the membrane wall [23,58,79].
- The passage of bubbles inferring a movement of fibres, what favours the fouling abrasion by contact of fibres [81] and increases the shear stresses close to the wall of membranes [82].

- The generation of shear stresses that could remove the fouling cake close to the wall of membranes was shown experimentally [82,86–88]. These shear stresses can be quantified by numerical simulation [92,93].
- The shear stresses in the bulk have an influence both on floc size [94,95] and on EPS concentrations [100,101].

To progress in the understanding of the process operation, it would be interesting to make a mapping which locates the TMP increasing rate depending on various parameters i.e. instantaneous flux, SS, SPM, SAD_m ; this would allow a comparative quantification of every phenomenon.

The fundamental understanding of local scale phenomena induced by aeration that occur at the membrane surface would also be useful to develop global MBRs model. As underlined by some authors [104] who tackled CFD issues, the natural progression for the development of an MBR CFD model would be the incorporation of bioreactions such as the activated sludge model (ASM). This seems to emerge as a trend and ASM based modelling of MBRs have recently been reviewed [105]. In a further step a global model linking operational parameters, biokinetics and transport/adhesion phenomena would be a powerful tool to manage MBRs, attempt has already been done [91] but there is still a need for more improvement.

4. Conclusion

Significant progress has been done towards SMBRs in the last years and the process has changed with time regarding structure (packing density, fibre diameter and length, etc.) as well as operating conditions (MLSS concentration, permeate flux and aeration). Some years ago the process was often operated with very high SS concentrations, up to 30 g L^{-1} whereas nowadays the concentrations are still higher than those of CASP but much lower than previously with a range of $6\text{--}20 \text{ g L}^{-1}$.

Filtration flux and sequencing management have already been widely investigated. Even if it is sometimes impossible to manage MBRs without backwashing, this operation has proved not to be of any great interest in terms of mean flux. Intermittent filtration with short relaxation time is more efficient because of the lower instantaneous fluxes it induces for the same water production.

More recently care has been taken to aeration parameters improvement. Aeration is more efficient when the operating conditions (high MLSS and permeate flux) generate fouling. As with hydrodynamics, aeration sequencing management is important: intermittent aeration, especially working with intermittent filtration, enables to save energy. But further work is required to lower the energy consumption involved by air sparging. It should be pointed out that there is a lack of standardised method to compare studies. This problem has already been mentioned in former reviews dealing with membrane fouling and it is also true for hydrodynamics and the characterization of aeration global effect. Similarly it is possible to find many studies that tackle the same parameter but given the wide range of operating parameters and MBRs configurations, comparing them would not be consistent most of the time. Finally there is a lack of real scale study and many pilots are run with synthetic effluent. It is thus difficult to provide an optimal operational setting even if the existence of a threshold of filtration efficiency related with airflow rate is demonstrated.

One strategy would be to find global trends that could be applied to all MBRs. More particularly, there is a need to quantify the predominant mechanism induced at local scale by aeration that improves the filtration performance, depending on operating conditions. These mechanisms are:

- Turbulences, which have a positive effect on the enhancement of back-transport. The membrane may also face more homogeneous hydrodynamic conditions because of the unsteady property of turbulent flow.
- Fibre movement, which would increase the probability for the membrane to benefit from air sparging and allow higher shear to be induced by the liquid.
- Air shear stresses, which can have both positive and negative impact: a balance must be found between the increase of shear stresses that will allow the removal of foulants sticking to membrane on the one hand, and the preservation of the mixed liquor integrity on the other hand.

At a wider scale, hydrodynamics and aeration homogeneity are of prime importance to produce even fouling distribution. The particular case of permeation flux mal-distribution along a hollow fibre is well known but the same behaviour has been observed at the global scale of SMBRs.

In conclusion, improving MBRs may require a double approach that would tackle the issue of local mechanisms and the design considerations. CFD may be also a powerful tool for this purpose and has already demonstrated its efficiency on the two cases. A further step would be the implementation of a global dynamic model that would enable the energy consumption of the process to be monitored. Attempts have already been made, combining biological and hydrodynamic conditions in a same model. However modelling difficulties due to phenomena involving different time scales required specific settings which limit the generalization of the whole process model. A better knowledge of the influence of local mechanisms and of the behaviour of biological media is expected to update these models and consequently increase the energy savings related to aeration.

Nomenclature

ASM	activated sludge model
CASP	conventional activated sludge process
CTA	constant temperature anemometry
CFD	computational fluid dynamics
EPS	extracellular polymeric substances
FS	flat sheet
HF	hollow fibre
J	filtration flux ($\text{L h}^{-1} \text{ m}^{-2}$)
J_b	backwash flux ($\text{L h}^{-1} \text{ m}^{-2}$)
MBR	membrane bioreactor
MLSS	mixed liquor suspended solids (g L^{-1})
MLVSS	mixed liquor volatile suspended solids (g L^{-1})
PIV	particle image velocimetry
PSD	particle size distribution
Q_g	airflow rate ($\text{m}^3 \text{ h}^{-1}$)
Q_p	permeate flux ($\text{m}^3 \text{ h}^{-1}$)
S_m	membrane surface area (m^2)
S_r	cross-sectional area of the membrane module (m^2)
SAD_m	specific aeration demand in $\text{m}^3 \text{ h}^{-1} \text{ air m}^{-2}$ membrane area
SAD_p	specific aeration demand in $\text{m}^3 \text{ h}^{-1} \text{ air m}^{-3} \text{ h}^{-1}$ permeate product
SMBR	submerged membrane bioreactor
SMP	soluble microbial products
SS	suspended solids (g L^{-1})
T	air/process temperature (K)
TMP	transmembrane pressure
U_g	superficial gas velocity (m s^{-1})

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