Novel magnetically induced membrane vibration (MMV) for fouling control in membrane bioreactors

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Abstract

Conventional submerged membrane bioreactors (MBRs) rely on the coarse bubbles aeration to generate shear at the liquid–membrane interface to limit membrane fouling. Unfortunately, it is a very energy consuming method, still often resulting in a rapid decrease of membrane permeability and consequently in higher expenses. In this paper, the feasibility of a novel magnetically induced membrane vibration (MMV) system was studied in a lab-scale MBR treating synthetic wastewater. The effects on membrane fouling of applied electrical power of different operation strategies, of membrane flux and of the presence of multiple membranes on one vibrating engine on membrane fouling were investigated. The filtration performance was evaluated by determining the filtration resistance profiles and critical flux. The results showed clear advantages of the vibrating system over conventional MBR processes by ensuring higher fluxes at lower fouling rates. Intermittent vibration was found a promising strategy for both efficient fouling control and significant energy saving. The optimised MMV system is presumed to lead to significant energy and cost reduction in up-scaled MBR operations.

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1. Introduction

Membrane bioreactors (MBRs) have been widely investigated as an advanced wastewater treatment. Their advantages over the conventional activated sludge systems have been widely cited throughout literature. However, their widespread application is still restricted, mainly due to the membrane fouling and its consequent capital and operational costs. Most traditional approaches for fouling control are based on optimizing operational conditions in favor of fouling mitigation, improving membrane properties and exploiting the hydrodynamics near the membrane surface (Le-Clech et al., 2006; Meng et al., 2009; Drews, 2010).

Hydrodynamic control is implemented via the cross-flow velocity in cross-flow MBRs, and as the secondary flow of the coarse air bubbles in submerged MBRs. Another technique is by moving the membrane itself relative to the feed, or by moving a mass near by the membrane surface. This technique is commonly known as dynamic or shear-enhanced filtration (Beier, 2008; Jaffrin, 2008).

In the submerged MBRs, the coarse bubbles aeration generates direct shear on the membrane surface by inducing a secondary flow of liquid that disrupts the mass transfer boundary layer, and promotes local mixing near the membrane surface (Cui et al., 2003). Despite the rather high-energy input, this approach produces relatively weak shear rates. In addition, a “plateau” in terms of flux improvement is reached at a certain air supply (Genkin et al., 2006). Moreover, it is difficult to ensure a homogeneous bubble distribution (Genkin et al., 2006; Wu et al., 2008) and aeration at higher...
velocities can change sludge properties and hence diminish the biomass floc stability (Rosenberger and Kraume, 2003; Drews et al., 2005).

Considering the limited efficiency of the coarse bubbles aeration in submerged MBRs, the enhancement of shear rate via mechanical means seems a potential option for fouling control. A couple of studies have investigated the performance of shear-enhanced filtration systems, such as the Vibratory Shear Enhanced Processing (VSEP) and Vibrating Hollow Fiber Modules (VHFM) (Genkin et al., 2006; Beier et al., 2006; Altaee et al., 2010; Beier and Jonsson, 2007, 2009; Low et al., 2009; Kola et al., 2011). In the VHFM systems, the membrane is vibrated by a separated vibrating engine that produces axial oscillations. Membrane and engine are connected via a sliding rod.

Although all the referred studies reported a significant improvement on both the critical flux (CF) and the sustainability of operation, they face numerous limitations: (1) the vibrating system is often restricted to a small range of vibration amplitudes and frequencies; (2) because of the membrane unit is separated from the vibration engine, the obtained yield of shear rates is somehow reduced, due to energy loss resulting from the mechanical contacts and their friction; (3) in most cases, filtration is run in continuous vibration mode, without the ability of changing the vibration parameters during the filtration operation, hence not able to adapt to the needs of the mixed liquor that might change over time.

In the present study, a novel magnetically induced membrane vibration (MMV) system is proposed as an alternative shear enhancement device for fouling control in MBRs. As the vibrating engine is integrated into the membrane module, and as movement is magnetically induced, it is expected to experience less friction, to consume less energy and to have a very flexible vibration control. One of the main advantages of MMVs compared to the other shear-enhanced filtration systems, is their high flexibility for varying the operation modes in real-time, such as changing vibration amplitudes without interrupting the filtration to allow an online optimisation of the filtration performance. The unsteady fouling behaviour coming from the dynamic changes in feed properties can thus be controlled by real-time manipulation of the vibration parameters.

To our best knowledge, no such system has been reported so far. In this study, the efficiency of the MMV system to control membrane fouling was investigated in a lab-scale MBR treating synthetic molasses wastewater. The impact of several operation parameters on fouling was studied, including vibration-related factors (e.g., vibrating power, mode and cycle), membrane flux and presence of multiple membranes arrangement. In addition, the cost efficiency of the lab-scale MMV system was furthermore estimated and discussed.

2. Materials and methods

2.1. Activated sludge and wastewater

The activated sludge used to inoculate the lab-scale high-throughput-MBR (HTML, Belgium; Bilad et al., 2011a) was obtained from a pilot-scale MBR in the Waterleau wastewater laboratory (Wespelaar, Belgium) treating the same molasses wastewater, as the HT-MBR. The feed solutions were prepared by diluting 0.45 ml/l of molasses stock solution. The characteristics of the feed were given in Bilad et al. (2011b). The diluted molasses solution was chosen as feed wastewater, because it does not require pre-fine screening, it has a good COD/N ratio and contains trace elements (Yan et al., 2010). The bioreactor was operated at room temperature (22°C) in a fed-batch mode during the parametric studies and continuous mode during the long-term filtration test.

2.2. Membrane preparation and cleaning

Two different flat sheet membranes were used during the experiments, a commercial chlorinated polyethylene membrane (KUBOTA, Japan) (PEK) and a commercial polyvinylidine fluoride membrane (Toray) (PVDFf). Both membranes were used to evaluate the effect of vibration on membrane fouling (Sections 3.2.1–3.2.2). Due to the limited amount of membrane material, PVDFf was used to investigate the vibration-related parameters (Sections 3.2.3 and 3.3) and PEK was used for the experiments with multiple membranes (Section 3.4). These membranes were potted as described by Bilad et al. (2011a). The active membrane surface area in each membrane was 0.016 m2. The SEM images of the membranes and their properties are summarized in Fig. 1 and Table 1 respectively.

After each experiment, the module was removed from the bioreactor tank. First, physical cleaning was applied by flushing the membrane surface with pressurised tap water for 10 min. Afterwards, permeability of the membrane was measured. Unless the permeability loss was less than 5%, the membrane was chemically cleaned with 0.5 g/L NaOCl solution for 3 h, resulting in quasi-complete membrane permeability recovery in all cases.

2.3. Experimental setup

A schematic diagram of the lab-scale MBR is shown in Fig. 2. The construction of the reactor system was similar to that of the HT-MBR developed earlier (Bilad et al., 2011a), except for the addition of the MMV system. The reactor had a working volume of 18.6 L and was virtually divided into aerated and non-aerated zones. In the former zone, two different aeration systems giving a total flow rate of 0.6 m3/h were provided: the fine bubbles aeration to provide soluble oxygen for the biological process, while the coarse bubbles aeration had a role in scouring the membrane surfaces as fouling control in a conventional submerged MBR system. In the non-aerated zone, a constant but weak movement of fluid was still present, induced by the air bubbles movement in the aerated zone.

In the MMV system, a magnetically induced vibration of the membrane is applied in order to provide shear at the liquid–membrane interface. The module consists of one or more membranes that is integrated in the MMV module. The system includes a vibration driver, an electric wire, a vibration engine and the actual vibrating module. The signal is provided by the vibration driver being installed with a Test
Tone Generator software (Esser audio, Germany). The vibration itself is created in the vibration engine by magnetic attraction/repulsion forces in a “push and pull” mode. The movement orientation of the vibrating part faces the narrow face of the module in order to both prevent the bumping of liquid onto the membrane and minimise the associated energy loss. The vibration moves the membrane to the left and the right through a sinusoidal pattern. The adjustable vibration parameters are the applied power (determined by combination of vibration amplitude and frequency), the vibration mode and the vibration cycle. The vibration amplitude and frequency can be supplied either with constant or variable values, while vibration can be run either in continuous or intermittent mode. During the filtration experiments, the vibration amplitude was limited to 2 mm at the most and the frequencies were adjusted between 0 and 60 Hz. The real vibration power ($P_{V,W}$) was later calculated in a first approximation from the electric current and electrostatic potential measured on the electrical wire by two AVO meters (DVM 890-Velleman, Belgium). Heat losses at the engine were thus included in the measurements.

2.4. Determination of sludge characteristics and filtration parameters

The mixed liquor suspended solid (MLSS), sludge volume index (SVI) and the feed and effluent quality were measured according to standard methods (APHA, 1992). The filtration performance was evaluated by determining the critical flux (CF) and filtration resistance values. The flux ($J$, L/m²·h) and membrane permeability ($L$, L/m²·h·bar) were calculated by using Eqs. (1) and (2), respectively:

$$J = \frac{\Delta V}{Ah} \tag{1}$$

$$L = \frac{J}{\text{TMP}} \tag{2}$$

where $V$ is the permeate volume (l), $t$ is the filtration time (h), $A$ is the membrane surface area (m²) and TMP the transmembrane pressure (bar, or Pa for filtration resistance calculation). The filtration resistance ($R_f$, m⁻¹) was calculated based on Darcy’s law (Eq. (3)):

$$R_f = \frac{\text{TMP}}{\eta J_V} \tag{3}$$

$$R_f = R_M + R_F \tag{4}$$

where $\eta$ is the dynamic viscosity of permeate (Pa·s), $J_V$ is the flow velocity (m/s) calculated from the flux, $R_M$ is the intrinsic membrane resistance (m⁻¹), and $R_F$ the fouling resistance (m⁻¹).

Two typical types of filtration were performed throughout the study. The first filtration type was the conventional aerated filtration. In this case, the membrane module was placed into the aerated zone and the filtration was performed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PE&lt;sub&gt;K&lt;/sub&gt;</th>
<th>PVDF&lt;sub&gt;M&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore size (using imageJ) (μm)</td>
<td>0.4</td>
<td>0.08</td>
</tr>
<tr>
<td>Pore size (supplier data) (μm)</td>
<td>0.22</td>
<td>0.03</td>
</tr>
<tr>
<td>Surface porosity (%)</td>
<td>11</td>
<td>0.2</td>
</tr>
<tr>
<td>Thickness (μm)</td>
<td>165</td>
<td>320</td>
</tr>
<tr>
<td>Morphology</td>
<td>Symmetric</td>
<td>Asymmetric</td>
</tr>
</tbody>
</table>

Fig. 1 – SEM images of surface and cross section of the membranes used in this study.
as in conventional submerged MBRs. The second filtration type was the vibrated filtration in which the membrane module was placed into the non-aerated zone, and the filtration was performed as a MMV system.

The CF (L/m² h) was measured using the stepwise method (Le-Clech et al., 2003). The applied initial flux, step height and step duration were 2 L/m² h, 2 L/m² h and 15 min, respectively. This method was chosen because of its technical simplicity. To obtain the CF value, the final TMP values after each step were plotted against the fluxes. Below the CF, a linear relationship exists and the CF was determined as the flux at which this linear correlation ceased to exist.

3. Results and discussion

3.1. Bioreactor performance

The acclimatization and biological performance of the sludge in the HT-MBR was discussed earlier (Bilad et al., 2011c). To prevent the accumulation of slowly biodegradable substances during the fed-batch operation, a part of the liquid in the reactor was discharged every week. The activated sludge was settled and a part of the supernatant was withdrawn and replaced with tap water. During the test, the MLSS concentrations were kept at 10–12 g/L by partially withdrawing the sludge, while the SVI was in the range of 55–75 mL/g. During the continuous operation, the hydraulic retention time was set at 24 h, to remove more than 98% of the chemical oxygen demand. No suspended solids were detected in the permeates for neither the aerated nor the vibrated modules. Comprehensive analysis of the biological performance was not carried out during this study, since the main objective — at the current stage — was to prove the effectiveness of MMV to control fouling.

3.2. Effect of vibration parameters on membrane fouling

3.2.1. Membrane fouling at different filtration modes

In order to observe the impact of the vibration on the filtration performance using MMV system, the filtration of the activated sludge was performed in four different modes.

- Mode-1: filtration in the non-aerated zone without vibration. In this mode, the fouling is only controlled by the limited movement of liquid induced by the aerated zone.
- Mode-2: subsequent filtration just after Mode-1 without cleaning the membrane. This mode was performed to observe the impact of vibration on cleaning a fouled membrane.
- Mode-3: filtration in the aerated zone (‘aerated filtration’). The coarse bubble aeration velocity was set at 0.3 m³/h.
- Mode-4: filtration in the non-aerated zone (‘vibrated filtration’).

For Modes-2 and -4, the membrane was continuously vibrated at a frequency of 50 Hz, corresponding to a PV of 12.5 W. The purpose of selecting a relatively high PV in this test was to observe the maximum impact of vibration. For all modes, filtrations were run at a fixed flux of 22 L/m² h for 30 min and the filtration performance was evaluated using the resistance profiles. The virtual division of the MBR zones is schematically shown in Fig. 2.

Fig. 3 shows the resistance profiles of the four different filtration modes. Mode-1 shows the highest filtration resistance followed by Mode-3, and -4, for both tested membranes. This order clearly represents the shear rates at the membrane surfaces. In the non-aerated zone, the membrane surfaces experienced very limited shear rates, only from some movement of the bulk liquid. In the aerated zone, a higher degree of shear rates was realized at the membrane surfaces due to both the liquid movement and the air bubbles scouring. In the case

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Fig. 2 – Schematic diagram of the (a) HT-MBR setup equipped with the MMV system, (b) MMV module in front view, and (c) MMV module in side view, showing the parallel position on the multiple membranes mounted.
of the vibrated filtrations, the shear rates were high enough to
develop the back transport from the membrane that finally
exceeded the fouling rate, thus promoting the removal of
colloids, macromolecules and other foulants from the
membrane surface. As a consequence, almost no fouling was
built-up in Mode-4 by both the PVDF<sub>e</sub> and PEK<sub>e</sub> membranes.

The impact of vibration to clean a fouled membrane is
clearly seen from the results of filtration in Mode-2. A signif-
ificant drop of filtration resistance was immediately obtained
just after the vibration started. This result confirms the ability
to be noticed that this experiment was performed in a very
short time span. Apart from the attachment of (bio)foulants,
many studies with vibrated membranes suggested that this shear rate strongly depends
on the vibrating parameters and is determined as a function of
both the vibration amplitude and frequency (Genkin et al.,
2006; Beier et al., 2006; Beier and Jonsson, 2007).

A series of filtration tests was performed at different
P<sub>V</sub>s, measured as the electric consumption by the vibration
engine, in order to investigate its effect on membrane fouling.
P<sub>V</sub> was varied by adjusting the frequency or amplitude of vibration and was set in the range of 0–13.8 W. The filtrations
were performed for 30 min at a fixed flux of 22 L/m<sup>2</sup> h, and the
final resistances at the end of each filtration are plotted
against P<sub>V</sub> in Fig. 4. Results suggest that the P<sub>V</sub> significantly
affects the filtration performance. In general, the higher the
applied electric power, the lower the fouling. A significant
coupling of filtration resistance was achieved at a P<sub>V</sub> of
10.7 W or higher. This P<sub>V</sub> value beyond which no further
coupling of fouling could be achieved is further referred to as
the critical power.

3.2.3. Effect of vibration strategies

3.2.3.1. Continuous vs. intermittent vibration. The effect of intermittent vibration on the filtration performance was
tested at a P<sub>V</sub> of 8 W and a J<sub>V</sub> of 22 L/m<sup>2</sup> h. P<sub>V</sub> was chosen just
below its critical value (Section 3.2.2) in order to detect even
small changes of the fouling rates among the different filtra-
tion tests. The experiments were carried out in three different
modes, all in the non-aerated zone: (1) filtration without
vibration, (2) filtration with vibration and (3) filtration with
intermittent vibration. The intermittent vibration consists of
idle and vibration phases to form a cycle. The sum of the idle
and vibration times in one cycle is defined as the total cycle
time (t<sub>C</sub>), and the ratio of the vibration time to the t<sub>C</sub> is defined
as the vibration ratio (α). In this particular filtration test, t<sub>C</sub> and
α were set at 60 min and 50%, respectively.

The results of different vibration strategies are presented
in Fig. 5. As expected, filtration with continuous vibration
gave the best performance, while the intermittent vibration
resulted in somewhat higher but still acceptable final filtra-
tion resistance. A much higher filtration resistance was
observed for the filtration without vibration. For instance, the
R<sub>T</sub> values of filtrations in modes (1), (2) and (3) after 300 min of
operation were found to be 84%, 13% and 43% of the R<sub>T</sub>,
respectively. A slow rise of filtration resistances for both
vibration-assisted filtrations suggests that the vibration in
MMV system can be operated in an intermittent mode, which
offers an adequate fouling control and a reduced energy
consumption.
3.2.3.2. Effect of intermittent cycle time. The performance of the MMV system can be further optimised by varying both the $t_C$ and $\alpha$. In these particular experiments, $\alpha$ was fixed at 50% and $t_C$ was varied. The $P_V$ and $J$ were fixed at 8 W and 22 L/m$^2$h, respectively. Fig. 6 shows that $t_C$ strongly affects the filtration performance. For the longest $t_C$ (120 min), a sharp rise of fouling resistance occurred during the idle phases and the membrane permeability was only partially recovered during the vibration phases. On the other hand, filtrations at shorter $t_C$ resulted in lower filtration resistances. The $R_F$ values of filtration with $t_C$ of 120, 24 and 4 min after 300 min of operation, were found to be 125%, 75% and 75% of the $R_M$, respectively. The lower fouling rates at shorter $t_C$ can be explained by the shorter idle phases, during which less aggressive fouling can be expected. This result confirms that the appropriate choice of $t_C$ for the MMV system is indispensable to ensure both an efficient and an economic operation.

3.3. Operation flux and critical flux

3.3.1. Effect of operation flux on membrane fouling

Flux is considered as one of the most important factors affecting membrane fouling in MBRs (Chang et al., 2002). Its appropriate selection is crucial to maintain the fouling rate at a satisfactory level during long-term operations. A series of filtrations was performed to investigate the effect of operational flux on filtration performance. The performances of both the vibrated filtration and the aerated filtration were compared, as shown in Fig. 7. The flux was varied between 14 and 30 L/m$^2$h, and the MMV system operated in an intermittent mode, with a $t_C$ of 4 min, a $P_V$ of 8 W and an $\alpha$ of 50%.

![Effect of intermittent cycle duration](image1)

![Effect of different membrane vibration strategies](image2)

![Effect of $P_V$ on final filtration resistance using (a) PVDF$_T$ and (b) PEK membranes.](image3)
As expected, a faster rate of fouling was found at higher fluxes for both systems. The filtration resistance at the corresponding fluxes was always found to be significantly lower for the vibrating module. However, the MMV system experienced a much lower fouling at the flux ranges of 14—26 L/m² h. These results suggest that the MMV system could ensure higher operational fluxes compared to conventional submerged MBR systems.

3.3.2. Effect of vibration on critical flux
Membrane fouling, in general, is managed by operating the system below its CF (Le-Clech et al., 2006). The CF is broadly defined as the maximum flux value, at which (theoretically) no particle deposition on the membrane surface occurs. This critical value depends on several factors such as the feed condition, membrane properties, hydrodynamics and operation conditions (Wu et al., 2008). The enhanced shear upon vibration can facilitate the increase of CF. Its correlation was evaluated by measuring CF values at different \( P_V \) (Fig. 8). The experiment was carried out at \( a = 100\% \) and at a constant vibration frequency of 50 Hz. The \( P_V \) was adjusted by varying the vibration amplitude.

Fig. 8 indicates that the higher the \( P_V \), the higher the CF, in accordance with the literature (Genkin et al., 2006; Beier et al., 2006; Altaee et al., 2010). For example, a CF value of 46 L/m² h was obtained at a \( P_V \) of 15.4 W, which is about 3 times higher than the CF measured for the similar feed and membrane in a conventional aerated lab-scale MBR (Bilad et al., 2011a). The \( P_V \) and CF were found to be proportional in the range of the studied \( P_V \). The intercept with the y-axis in Fig. 8 gives the CF for the non-vibrating operation. Since the MMV system is operated at a fixed frequency, \( P_V \) is proportional here to the applied vibration amplitude, and that is in line with earlier findings for the VHFM system (Beier et al., 2006).

3.4. Long-term filtration, multiple membranes operation and energy consumption

The applicability of the MMV system to control membrane fouling in short-term filtration duration has been proven in the previous sections. However, a filtration test over an extended time frame is indispensable to provide more convincing results. In the following experiments, the activated sludge filtration was studied from two different aspects: (1) examining the long-term filtration resistance profile and (2) investigating the effect of multiple membranes in the MMV system to allow evaluation of the energy consumption.

3.4.1. Long-term filtration
Since the membrane used is different from the one used in Sections 3.2.3 and 3.3, preliminary experiments were performed to select the optimum values for \( t_C \), \( a \) and \( P_V \). In order to better represent the full-scale operation, the filtration was now performed with a relaxation time included in the intermittent filtration. The choice of filtration cycle duration and ratio was also based on a preliminary experiment in which both of these parameters were varied. The results of the aforementioned preliminary experiments are provided as Supplementary material.

For the long-term filtration, the filtration was operated in a 5 min cycle that consisted of 4.5 min of filtration and 0.5 min of relaxation. The experiment was performed in two sequential runs. Initially, 5 PEK membranes were run in parallel. Two membranes were operated in the aerated zone, and 3 membranes were operated with vibration. The distance between the membranes in the MMV system was about 5 mm. The operational parameters \( J \), \( P_V \), \( t_C \) and \( a \) for the MMV were set at 16 L/m² h, 6.4 W, 5 min and 50%, respectively. The applied flux was selected as the flux generally applied for the particular membrane in full-scale applications, and the \( P_V \) was obtained as the result of a preliminary test. \( P_V \) was set to be low enough to reduce energy consumption, but high enough to provide an acceptable fouling control.

Fig. 9 shows the profile of the filtration resistances during the long-term filtration. After seven days of operation, fouling was found to be more severe for all modules in the vibrated system compared to the ones in the aerated system. This is an obvious contradiction with all the previous results, but can be explained by the arrangement of the membranes. The strongest resistance increase was observed in the case of the vibrated membrane in the second position (i.e. situated

![Fig. 7](image_url)  — Effect of operational flux on filtration resistance in (a) aerated system and (b) MMV system.
between the two others), suggesting an inappropriate distance between the membranes. Apparently, the membranes in the MMV system were situated so near to each other that the liquid between the membranes moved in-phase and almost became stagnant, moving together with the membrane. To confirm this hypothesis, the filtration was stopped, the second (middle) vibrated membrane was omitted from the reactor, and the filtration was continued. The remaining membranes were chemically cleaned prior to the filtration re-start.

Fig. 9 clearly shows that the two vibrating membranes (now with a distance of 10 mm in between) performed better in terms of fouling than the aerated ones throughout the 15 extra days of operation, even though membrane 3 showed a jump on days 13–16 which cannot be explained. These results not only confirm the efficacy of the MMV system in a long-term filtration process, but also suggest the importance of adequate design and arrangement of the membranes in one module.

3.4.2. Multiple membrane operation and energy consumption
The reduction of energy consumption associated with fouling control is currently one of the main objectives in MBR research. The energy consumption of submerged MBRs is several times higher than that of conventional activated sludge processes (Cornel et al., 2003), and it mainly comes from the energy associated with the coarse bubble aeration for fouling control (Gander et al., 2000). The use of MMV system might offer a promising alternative as a new approach to control fouling in the MBRs. In most shear-enhanced filtration systems, the energy consumption (ED, kWh/m³) is dominated by the energy that is consumed by the vibration engine. Therefore, the energy consumption associated with the MMV system was monitored during this particular test. However, since the ED is calculated based on the volume of permeate, the scale of the plant becomes very significant, mostly favoring large-scale applications. To evaluate the ED of the MMV system, the filtration with multiple membranes was conducted. The MMV system was loaded with up to 6 membranes, to check if there were any changes in filtration performance when the number of membranes in the module increased.

Six filtration runs with activated sludge were performed with the MMV system, with each time a different numbers of membranes attached to the module. One additional filtration with six membranes in one module was also performed without vibration for comparison. The filtration parameters were set at $J$ of 16 L/m² h and $P_v$ of 6.4 W, similar to the values used in the long-term test.

The profile of the resistance of filtration with different numbers of membranes on the MMV system is shown in Fig. 10. The filtration resistances are given as the average values and the deviations are represented by the shaded area. The results suggest that the lab-scale MMV system could...
sustain with at least six membranes (each has 0.016 m² effective area). The addition of up to six membranes did not significantly affect the filtration performance. This result is in line with the new generation of VSEP system, where increasing the membrane area does not significantly affect the ED (Jaffrin, 2008). The addition of more membranes to the MMV system was not feasible in the current setup, due to the limited space available inside the lab-scale reactor tank.

The available information on energy consumption of full- or pilot-scale MBRs in scientific literature is scarce. Table 2 contains some related data of selected publications from the last 5 years and furthermore includes ED data from the lab-scale MMV system. The ED associated with the MMV system was calculated by using a J, P, V and α of 16 L/m² h, 6.4 W and 50%, respectively, similar to the ones used in the long-term test.

Table 2 also confirms that the ED associated with coarse bubble aeration is strongly affected by plant scale. The ED of the pilot-scale MBR (Fenu et al., 2010) is almost 10 times the one of the full-scale ones. This should be considered when analyzing the lab-scale MMV system data. Calculating the ED using six membranes (2.03 kWh/m²) gives a 6 times smaller value than with one membrane (12.12 kWh/m²). Nevertheless, this value is much lower than the ED of a pilot-scale MBR that operates with a ±160 time larger membrane area, suggesting a rather economic design of the system, despite being far from optimized yet. It is worth noting that the ED of the lab-scale MMV system is about 3.5 times higher than the ED of the best performing full-scale MBR listed in Table 2. However, direct comparison of these data is not entirely reliable, since the ED a lab-scale setup is not of economical scale and the feed and sludge characteristics of an MBR have a serious influence on the filtration performance. From these comparisons, it can thus be expected that an optimised MMV system (frequency, amplitude, vibration cycle, etc) may lead to a significant cost reduction for fouling control in MBRs. With even membrane moving in one direction and odd membrane in the other, more compact, but still efficient modules could possibly be realized.

Table 2 – Energy demand of lab-scale MBR and comparison with literature data.

<table>
<thead>
<tr>
<th>Reactor (membrane)</th>
<th>ED (kWh/m³)</th>
<th>J (L/m² h)</th>
<th>A (m²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab-scale MBR (KUBOTA flat sheet)</td>
<td>12.12a</td>
<td>16</td>
<td>0.016</td>
<td>Present study</td>
</tr>
<tr>
<td></td>
<td>2.03b</td>
<td></td>
<td>0.096</td>
<td></td>
</tr>
<tr>
<td>Pilot-scale MBR (KUBOTA flat sheet)</td>
<td>6.06</td>
<td>19</td>
<td>16</td>
<td>Fenu et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>4.88</td>
<td></td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Full-scale MBR (Zenon hollow fibre)</td>
<td>0.64</td>
<td>23</td>
<td>10,160</td>
<td>Fatone et al. (2007)</td>
</tr>
<tr>
<td>Full-scale MBR (Zenon hollow fibre)</td>
<td>&lt; 0.60</td>
<td>26</td>
<td>12,130</td>
<td>Verrecht et al. (2010)</td>
</tr>
<tr>
<td>Full-scale MBR (hollow fibre)e</td>
<td>1.07</td>
<td>20</td>
<td>63,366</td>
<td>Gil et al. (2010)</td>
</tr>
</tbody>
</table>

a Calculated from F, with one vibrating membrane in the reactor.
b Calculated from F, with six vibrating modules in the reactor.
c Theoretical setup for cost sensitivity analysis.

during the number of membranes mounted in the MMV system was increased from one up to six, while increasing treated water volumes 6-fold. The MMV-aided filtration, after process optimisation, is expected to lead to significant cost less membrane area to be installed when taking advantage of the higher CF and energy (especially when expending the number of membranes per module) reduction in (up-scaled) MBRs. This novel membrane fouling limitation method seems very promising in MBRs, but also for the currently progressing anaerobic MBRs where coarse air bubbling is not an option, and possibly also other fouling sensitive ultrafiltration and nanofiltration operations, like algae harvesting.

4. Conclusions

Innovative magnetically induced membrane vibration proved very promising in a lab-scale MBR treating synthetic wastewater treatment. Results of both the filtration and the CF measurements showed clear advantages of this system over conventional MBR processes in terms of realisable flux and fouling control. Significant improvement of CF was obtained due to the enhanced shear at the liquid–membrane interface. The filtration was found sensitive to several operation factors such as the vibration parameters (e.g., vibration power and cycles) and the applied flux. The long-term experiments confirmed the efficacy of the MMV system, but also suggested the importance of an appropriate membrane arrangement in the MBR in the module. The energy demand of vibration, resulting in the highest of all the MBR costs, was found practically constant when the number of modules mounted in the MMV system was increased from one up to six, while increasing treated water volumes 6-fold. The MMV-aided filtration, after process optimisation, is expected to lead to significant cost less membrane area to be installed when taking advantage of the higher CF and energy (especially when expending the number of membranes per module) reduction in (up-scaled) MBRs. This novel membrane fouling limitation method seems very promising in MBRs, but also for the currently progressing anaerobic MBRs where coarse air bubbling is not an option, and possibly also other fouling sensitive ultrafiltration and nanofiltration operations, like algae harvesting.

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Abbreviations and symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>membrane surface area (m²)</td>
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<tr>
<td>CF</td>
<td>(normalised) critical flux (L/m² h)</td>
</tr>
<tr>
<td>ED</td>
<td>energy demand (kWh/m³)</td>
</tr>
<tr>
<td>J</td>
<td>permeate flux (L/m² h)</td>
</tr>
<tr>
<td>J₀v</td>
<td>permeate flow velocity (m/s)</td>
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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.watres.2011.10.026

References


L membrane permeability (L/m² h Pa)
MBR membrane bioreactor
MLSS mixed liquor suspended solid (g/L)
MMV magnetically induced membrane vibration
NF nanofiltration
Pv vibration power (W)
PEK polyethylene (Kubota)
PVDF polyvinylidene fluoride (Toray)
rf fouling resistance (m⁻¹)
rM intrinsic membrane resistance (m⁻¹)
RT filtration resistance (m⁻¹)
t filtration time
TC vibration cycle time (min)
TMP trans-membrane pressure (Pa)
SVI sludge volume index (mL/g)
UF ultrafiltration
ΔV permeate volume (L)
α intermittent vibration fraction (%)
η dynamic viscosity of permeate (Pa s)