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The effect of various high-frequency powerful vibration (HFPV) types on fouling control of hollow fiber membrane elements in a small pilot-scale SMBR system

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ABSTRACT

During the last decade in Europe, membrane bioreactor (MBR) systems have been proven to be a very efficient technique for municipal and industrial wastewater treatment (WWT). The most obvious appeal of the MBR technology is that it produces a stable and excellent effluent quality and eliminates the need for good sludge settleability, as it is one of the basic requirements in conventional WWT plants. Due to both the compact footprint and the great potential for automation, MBR plants ensure precise control of the sludge residence time and the mixed liquor suspended solids, which are basic operating parameters. The above results in: (a) the reduction of the required reactor size, (b) the promotion of the evolution of specific nitrifying bacteria, and finally, (c) the production of less sludge. However, the effluent rate of MBRs is limited, mainly because of the membrane fouling effect. Membrane fouling is probably the most critical problem of the submerged membrane bioreactors (SMBRs), and the applied techniques to avoid this problem have as a drawback the high energy that is needed and finally the production of chemical wastes. A lot of lab studies have been published concerning the impact of mechanical action on the removal of foulants from the membranes (e.g. vibration, buck-pulse, and ultrasound). The scope of this study is to examine the feasibility of high-frequency powerful vibration (HFPV) technique, as an alternative cleaning method, applied on fouled membrane elements in a continuous operated small pilot-scale SMBR unit, treating a novel synthetic wastewater (SWW). In this work, the implementation of various HFPV types (using commercial pneumatic vibrators) on identical, parallel hollow fiber (HF) fouled membranes, showed the following: (a) a repetitive pattern for transmembrane pressure and flux values vs. time; (b) the ability to select the proper vibration type according to the fouling extend on membranes; (c) the

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efficiency of this technique on membrane cleaning, in a membrane module system. After HFPV implementation, this system tends to have similar behavior with that of using new membrane modules. The HFPV technique seems to be very promising with respect to energy savings, compared to conventional air cleaning systems in SMBRs because it contributes to a low air-scouring operation due to the periodic and proper HFPV implementation. Moreover, this technique copes with the handling of membrane fouling in SMBRs units, using continuous MBR operating mode.

Keywords: Membrane bioreactor; Membrane fouling; High-frequency powerful vibration

1. Introduction

MBRs in wastewater treatment (WWT) processes have a variety of advantages over conventional biological ones including smaller footprint, stable and fine treated water quality, lower excess sludge production, and improved process-control of operation for changing loading conditions with respect to solid and hydraulic retention times. Additionally, the current legislation on the quality of the effluent disposal in combination with the decrease in membrane costs makes the MBR technique a globally accepted treatment process in the last years [1].

However, the major disadvantage of MBRs is the membrane fouling, due to concentration polarization, colloids adsorption, cake build-up, and biofouling [2]. Membrane fouling control remains the most critical issue in the successful application, cost-efficient operation, and it is the key for the steady operation of submerged membrane bioreactors (SMBRs) [3–5]. Also, it is one of the most challenging issues facing further MBR development [6–8]. The introduction of SMBRs has significantly reduced the energy consumption associated with reactor operations compared to side-stream MBRs [9], resulted in the acceleration of the application of MBR in WWT. Nevertheless, membrane fouling is the main obstacle that affects the performances of membranes retaining, the spreading of the MBR method. The fouling process causes a sharp increase in the transmembrane pressure (TMP) which leads to a reduction in the effluent flux, especially when the MBR system is operating under constant flux condition and finally to an irreversible condition of clogging.

Increasing the shear rate at the membrane surface (with gas sparging and liquid recirculation) and performing backwashing are frequently used techniques to reduce and remove the deposition of particles, colloids, and macromolecules. However, the fouling removal efficiency can be limited due to the difficulty in achieving good air flow distribution in highly packed membrane modules or in the presence of a high solids concentration in the bioreactor. Thus, a significant proportion of aeration and pumping energy is dissipated and for this reason, the expected shear force does not reach the vicinity of the membrane surface [10]. Therefore, energy consumption by aeration systems for fouling control remains the basic problem [11]. In addition, the application of aeration is generally undesirable in some specific applications such as anaerobic process in MBR systems, so it is important to retain the dissolved oxygen concentration at low level. On the other hand, the use of hydrodynamic shear stresses on the membrane surface is recognized as one of the most effective techniques on the limitation of the fouling formation [12].

Given the fact that the performance of any membrane process is a function of the membrane properties, and the hydraulic and operating conditions, researchers tried to use new techniques to relieve or minimize fouling phenomena. The most well-known mechanical techniques used amongst others are pulsed flow, air bubbling, low-frequency vibratory systems [12,13], mechanical mixing [14], low-frequency ultrasound [15,16], air lift provisions, and rotating systems [17–19]. A lot of experimental efforts have been made introducing low-frequency vibration of membranes or modules, as a very promising and effective method that gives very good results in combination with the right selection of the appropriate type of membrane and material.

The principle of "vibratory membrane filtration" was introduced from Pall Company 25 years ago as the Pallsep VMF filter. Since then, a lot of ideas have been suggested in this direction on the combination of conventional purification techniques together with mechanical actions and methods. The concept of vibratory shear-enhanced processing (VSEP) was firstly proposed by Armando et al. [20] and has been commercialized by New Logic Research, Inc. The process utilizes torsional vibration to vibrate annular flat sheet membranes. In their work, Low et al. showed with a VSEP L-series, that with high vibration amplitude/frequency applied in submerged HF membranes, the permeate flux could be maintained longer at higher fluxes [21]. They evaluated the effect of vibration with a frequency of 70 Hz and 19 mm amplitude in a sludge feed with mixed liquor suspended solids

(MLSS) of 1,800 mg/L, and they found out that the mechanical vibration gave the HF membrane a relatively "clean" condition and kept the permeate flux close to that of the clean membrane. In another case of a vibrated HF module, Genkin et al. [22] evaluated the effect of vibration with a range of 0–10 Hz frequency and 0–40 mm amplitude in a feed solution of unwashed baker's yeast and coagulant addition on the filtration performance of the submerged HF membranes. They found that the vibrational motion on the membranes has the potential to overcome the hydrodynamic limitations of the submerged concept. Beier et al. [23] also carried out experiments with a vibrating HF membrane module using suspensions baker's yeast in a frequency of 25 Hz and amplitude of 0.7 mm under low feed flow. They confirmed that critical flux can be increased with vibration frequency and amplitude as compared to air-scouring [24]. A slight variant of the foregoing technique, investigated by Altaee et al. [25], uses a vibrating mechanism consisting of a mechanical device attached to the top of the setup converting the rotating motion of the electric motor to vertical oscillations. The experiments carried out with a pair of HF membranes into a baking yeast solution with a vibration frequency varied between 1.67 and 6.68 Hz and amplitude of 40 mm. They concluded that the effect of membrane vibration on the critical flux was evident, especially at high vibrating speeds. This was due to the increase in shear force at the membrane–water interface, which in turn enhanced the particles' back diffusion mechanism. Similarly, Bilad et al. [26] created a magnetically induced membrane vibration mechanism to apply vibration on the membrane. In the same work, two different flat sheet membranes were used into a molasses wastewater solution with a vibration frequency varied between 0 and 60 Hz and amplitude of 2 mm. The vibration which is created in the vibration engine by magnetic attraction/repulsion forces in a "push and pull" mode moves the membrane to the left and the right through a sinusoidal pattern. According to the authors, results of both the filtration and the critical flux measurements showed clear advantages of this system over conventional MBR processes in terms of realizable flux and fouling control. Li et al. [27] used a crank mechanism attached to a motor to create vertical reciprocating movement. HF membranes vibrating at moderate frequencies (0–15 Hz) and amplitudes (0–12 mm) were submerged vertically in a bentonite solution. Experiments were conducted at both constant permeate flux and constant suction pressure conditions. They concluded that the membrane performance can be greatly improved when the vibration frequency or the vibration amplitude increases beyond a threshold magnitude. Kola et al. [28] observed that flux enhancement of submerged HF membrane system was achieved by imposing rotationally oscillating fluid or transverse oscillating membrane motion. The transverse vibration in the system generates the shear as well as secondary flows, contributing to fouling limitation even at low displacements (<5 mm) and frequencies (<21 Hz). Transverse vibration limits cake formation by focusing shear forces more directly on the membrane surface rather than recirculating the bulk fluid. The substantial benefits of transverse vibration on fouling limitation were observed in terms of critical flux improvement for macromolecular (alginate), particulate (yeast, bentonite), and anaerobic bioreactor solutions for 0.04 μm PVDF (polyvinylidene difluoride) membrane.

Although, all the referred studies reported a significant improvement on both the permeate flux, TMP, and the sustainability of operation, they face numerous limitations such as: (a) the vibrating system is often restricted to a small range of vibration amplitudes and frequencies, due to the lack of antivibration devices on the holding system of the membranes; (b) the shear rates were somehow reduced due to energy loss resulting from the mechanical contacts and their friction; (c) in most cases, the filtration process was performed at a fixed vibration mode without the ability of changing the vibration parameters during the filtration or cleaning process and addressing real application needs, where the mixed liquor might change over time; (d) in most studies, the offered vibration power was limited; experiments were performed in a very short time span of few minutes or hours; (f) detection limits of the used measuring devices were limited or measurements based on estimations (e.g. measurements that relate to the speed of the suction pump and not the actual flow); (g) in most cases, real or simulated waste water was used as an influent; (h)little research was done to examine the impact on different material and type of membranes; (i) the already examined cleaning systems and techniques are not feasible to be used in currently known SMBR modules, especially due to the large vibration amplitude; (j) in some cases, the MLSS concentration was very low; and (k) in many cases, experiments were handled without the recommendation by the manufacturer's membrane relaxation period that is essential due to the membranes construction material.

The SMBR unit used in this study, comprised small copies of commercialized filter elements working under a low aeration mode, in order to study the membrane fouling effect, in a relatively short time period. After running the unit for a long time period, when fouling occurs (accumulation of colloidal, and particulate species on or within the membrane pores) leading to a deterioration in membrane permeability, various high-frequency powerful vibration (HFPV) types were applied on three identical, parallel hollow fiber (HF) membrane elements via two different in-power commercial pneumatic vibrators. These vibration types give specific vibration characteristics (frequency, displacement, acceleration, etc.) to the membrane modules and their effectiveness on filter fouling control was monitored continuously via TMP and flux parameters vs. time without interrupting the operating mode of the whole SMBR unit.

The purpose of this work was to introduce a new approach of applying various types of HFPVs on HF membrane elements operating continuously in a pilot-scale SMBR unit, via pneumatic vibrators and investigate their impacts on the membrane fouling control, compared with the conventional air-scouring method.

2. Materials and methods

2.1. Synthetic wastewater

Strong synthetic wastewater, in terms of organic load was used and its components have been presented elsewhere [29]. Activated sludge obtained from a municipal conventional wastewater plant was also used to inoculate the biomass used in the pilot unit. The composition of the SWW was selected from the theoretical contribution of each element to give a ratio of COD/N/P (approx. 100:5:1) and laboratory analytical tests were made to confirm this ratio. The synthesis of SWW supplemented with minerals and trace elements such as K, Fe, Cu, Mn, Zn, Ca, and Mg.

2.2. Membrane module's properties

Specifications of the membrane elements used in the pilot plant are shown in Table 1. HF membrane elements were small copies of production models prepared from manufacturer for our lab unit.

2.3. SMBR pilot system description

The SMBR pilot system and the description of the vibration system have been presented elsewhere [29]. In the present experimental procedure, two types of pneumatic ball vibrators were used.

The first type was a small vibrator (K8-K) in a range of frequencies of 425–583 Hz (25,500 rpm at 2 bar–35,000 rpm at 6 bar), and the second type was a bigger vibrator (K16-K) in a range of frequencies of 217–325 Hz (13,000 rpm at 2 bar–19,500 rpm at 6 bar) according to the manufacturer data.

The vibration experiments took place during relaxation period of filtering process. The vibration moves the membrane in a powerful way to all directions as it is measured with laser Doppler vibrometer (Fig. 1). The desired module amplitude and its frequency of vibration of each of the two vibrators used (K8-K and K16-K) may be adjusted either by the pressure and/or by means of compressed air flow to the vibrator header. Vibration could be applied in a continuous or an intermittent scheduled mode.

2.4. SMBR experimental conditions

The SMBR pilot-scale system was operated for a period of more than 200 d, giving the biomass steady-state operating conditions, for the running experiments in this study. MLSS was maintained in a range of 7,500–10,000 mg/l and TMP values, for membrane modules, were held lower than 200–250 mbar, according to manufacturer's instructions. The SMBR system was regulated to operate under low air-scouring conditions and at a fixed pump speed (i.e. under a constant flux), in order to achieve a simulated adequate membrane fouling in a relatively short time. The air-scouring flow was set to 1/3 of the manufacturer's instructions, giving air supply of 1.5–2 L/min for all the three HF membranes per module. Moreover, no backwash cleaning procedure took place in this study.

A graphical linear correlation between the basic operative vibration parameters acquired the filter modules, with respect to the air pressure supply of the vibrators (ranged from 1 to 6 bars, measured just before the filter modules) was recorded (Fig. 2).

Air pressure supply for the vibrators K8-K and K16-K was selected to be 4 and 3 bars, correspondingly (approx. to the mean range each of the examined vibrators, ones). The module's acquired vibration operative parameters, at the above selected air pressure supplies, are given at Table 2. Measurements with the above vibrators were made under real condi-

Table 1
Specifications of the HF membrane elements

Filtration type	Membrane material	Pore size (μm)	Membrane area (m^2)	Type
UF	PVDF	0.1	0.05	HF

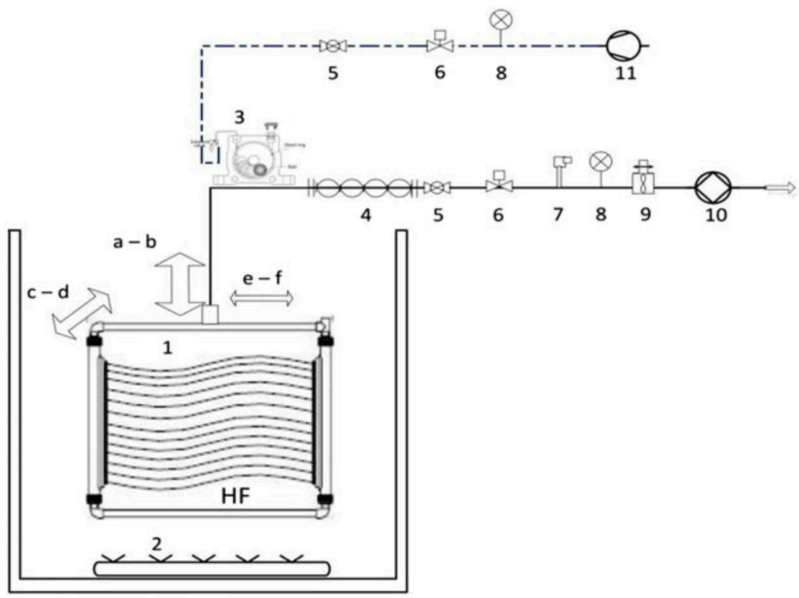

Fig. 1. Schematic overview of the pilot device and the powerful vibrational moves (a-b, c-d, e-f) of the HF membranes. Notes: (1) membrane element, (2) air diffuser, (3) pneumatic ball vibrator, (4) anti-vibration flex connector, (5) Regulator valve, (6) solenoid valve, (7) pressure transmistter, (8) pressure gauge, (9) flowmeter, (10) permeate suction pump, and (11) air compressor.

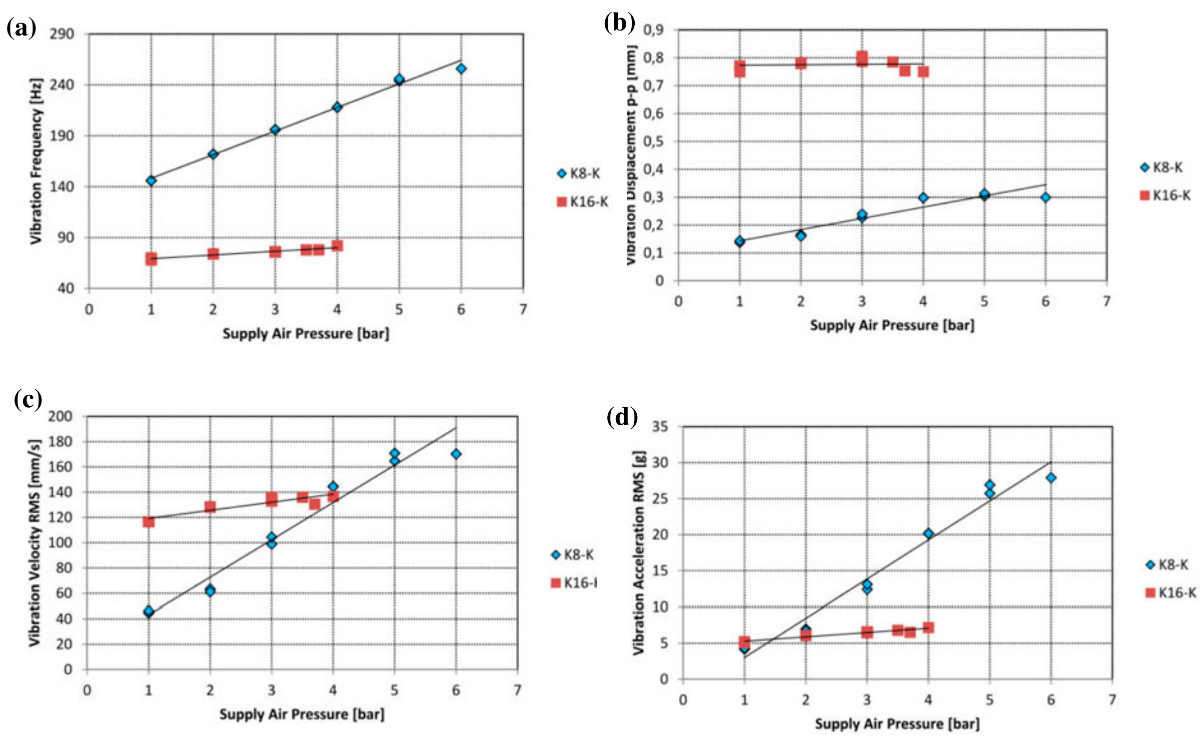

Fig. 2. Filter module vibration operative parameters (measured with Laser Doppler vibrometer) with respect to air supply pressure of each vibrator attached: vibration frequency (a), vibration displacement (b), vibration velocity (c), and vibration acceleration (d).

tions and the producing results can be used later in a scale-up attempt.

3. Results and discussion

The experimental work for testing and the evaluation of HFPV implementation on HF membrane fouling control was done by continuous monitoring of the TMP and permeate flux of effluent vs. time and lasted 28 d (28 d experiment). Four identical, new, in a parallel arrangement HF membrane elements (A1, A3, A4, and A6), were used divided in two sets A1 and A4 (first set), and A3 and A6 (second set), in the SMBR unit to study the comparative membrane's behavior in terms of TMP and flux monitored values vs. time, when various types of HFPVs were applied. These values were additionally confirmed by measuring manually the effluent volume (flux) and using mechanical glycerin gauges transmembrane pressure. All the presented values are normalized to a standard temperature of 20˚C.

In the first phase of the experiment (days 1–14), all membranes worked without vibration as reference membranes (see Figs. 3 and 4). The first membrane A1 presented a slightly worse performance, probably because it is the first from the MBR tank surface, where air-scouring conditions might be a little less. Implementation of vibration was applied in all membranes after the 14th d, where the TMP values for all membranes exceeded the prescribed upper limit value of 180 mbar. Three different vibrating types were applied as follows:

(1) Type 1 vibration using K8-K vibrator for 5 min (VT1);
(2) Type 2 vibration using K16-K vibrator for 5 min (VT2) and;
(3) Type 3 vibration using K8-K vibrator for 10 min (VT5).

On day 14, according to Figs. 3 and 4, flux mainly of A1 and A3 membrane decreased significantly to about 6 L/m^2 h (low set value) and 7.65 L/m^2 h, respectively, while the TMP values of all membranes reached almost 180 mbar. At this time, simultaneously, HFPVs were almost implemented in all membranes. In membrane A1 (& A4) vibration type 1 (VT1) was applied, whereas in membrane A3 (& A6), vibration type 2 (VT2) was applied (second phase of the experiment, days 14–28).

Fig. 3 shows the TMP and permeate flux profiles of A1 membrane vs. time under the first VT1 implementation that was started during day 14, and was repeated three times, with intervals of almost two hours, each time that TMP values reached the initial (180 mbar). During the first vibration, flux almost doubled from 6.45 to 12.75 L/m^2 h, while the TMP value was reduced significantly (from 183 to 127 mbar). After the second and third implementation of VT1, a repeatable effect was observed, in which the membrane needs further cleaning after about two hours time. Thus, it was decided to apply a vibration type giving longer implementation time i.e. from 5 to 10 min (VT5), in order to examine the behavior of the two different types of vibration. The first VT5 implementation on A1 membrane presents a more positive contribution effect to the above parameters (TMP reduction from 183 to 103 mbar whilst flux increase from 9.75 to 17.4 L/m^2 h). This led to the operation for three days (day 14 to day 17) until the pressure rises back to upper limiting levels (180 mbar). The experiment was repeated on day 17, by a second VT5 implementation with better results (this led to the operation for nine days–day 17 to day 26) as shown to Fig. 3. Almost the same behavior presents the A4 HF membrane.

The TMP and permeate flux profiles of A3 HF membrane vs. time under the first VT2 implementation at 14 d as mentioned above is shown in Fig. 4. It is observed that with respect to the A1 (& A4) case, here, we have much better effect of this vibration type lasting about 4 d till flux reduced to a low value 8.25 L/m^2 h and TMP rise to 135 mbar. In addition, the reduction in TMP value, just after the HFPV implementation, was more than three times lower (from 175 to 48 mbar) and flux increased almost three times from 7.65 to 20.25 L/m^2 h. The second VT2 implementation on A3 (& A6) membrane took place on day 18 for comparison with membrane A1 and A4,

Table 2
Operative vibration parameters measured on HF membrane elements

Vibrator type	Compressor's pressure (bar)	Vibrator's supply air pressure (bar)	Vibration frequency (Hz)	Vibration velocity RMS (mm/s)	Vibration acceleration RMS (g)	Vibration displacement p-p (mm)
K8-K	7	4	223	142	20	0.3
K16-K	5	3	76	134	6.6	0.78

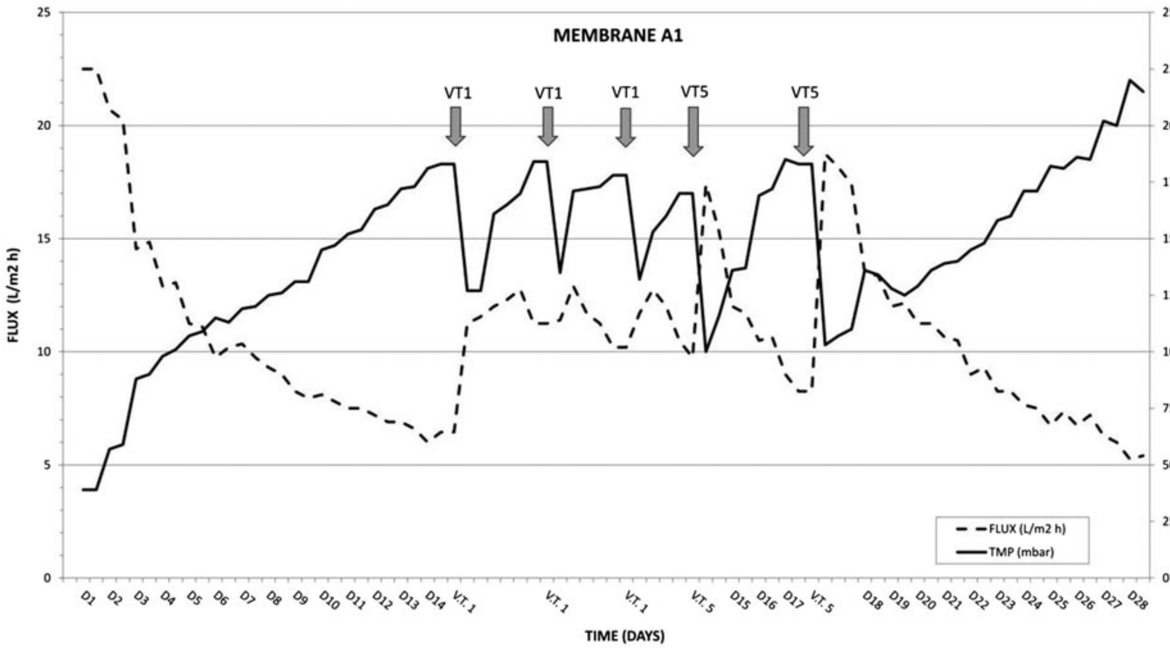

Fig. 3. TMP and permeate flux profiles vs. time on A1 HF membrane after HFPV implementation.

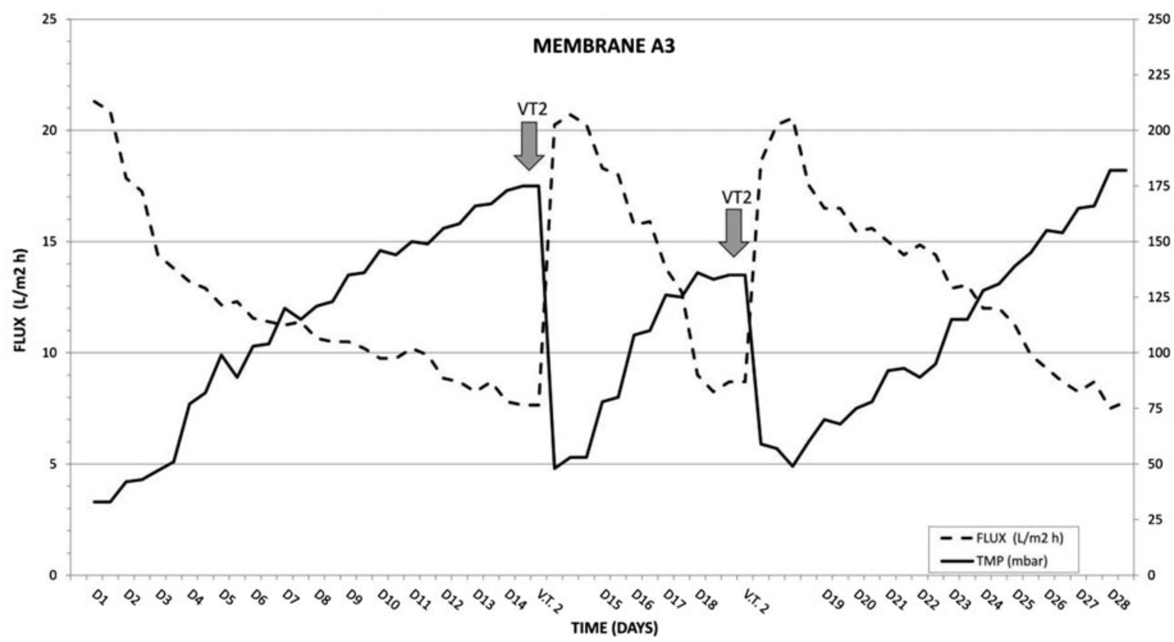

Fig. 4. TMP and permeate flux profiles vs. time on A1 HF membrane after HFPV implementation.

reasons. This increased the flux from 8.7 to 20.55 L/m^2 h, while the TMP value was reduced again from 135 to 49 mbar. After that, operation characteristics were recorded until the prescribed limits of high or low values for TMP and flux were reached. According to Fig. 4, TMP exceeded 135 mbar (139 mbar) after 7 days and 175 mbar (182 mbar) after 10 days.

Respectively, flux decreased to 8.25 L/m^2 h in 9 days and to 7.65 L/m^2 h in 10 days, where at this time another HFPV will be needed. It should be noticed that the second VT2 implementation on A3 (& A6) membrane gave the same pattern of TMP and flux vs. time just after the first three days of the implementation

(Fig. 4). Almost the same behavior presents the A6 HF membrane.

4. Conclusions

The HFPV technique (for fouling control) applied in this study on HF membranes in a small pilot-scale SMBR system treating SWW was found to be very promising. HFPV performance seems to be very high, returning the performance of the fouled membranes almost to the cleaned ones, in terms of TMP and flux measuring values.

The repeatability of the VT1 and VT2 vibration types was very adequate when applied on the same membrane types with similar fouling condition. The VT5 vibration type vs. VT1 on the same membrane type gives better results, elongating the time period for the next HFPV application from two hours to three days). Finally, the VT2 implementation from the start of the fouling procedure presents excellent fouling control results, giving even 10 days time period for the next HFPV application. The repeated vibrations in all the four membranes showed a stable management in terms of maintaining TMP and flux values in permissible and desirable levels, demonstrating the successful impact of vibration schemes used on fouled membranes. The energy benefit using vibration techniques for preventing membrane fouling seems to be very high, compared to the conventional process of an intense air-scouring used to clean membranes throughout the whole process. In addition, this lower aeration should also help to minimize the excess dissolved oxygen (DO) that returns to anoxic tank via the mixed liquor from membrane tank, which typically contains DO at high levels, decreasing significantly the denitrification efficiency.

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