Application of high frequency powerful vibration (HFPV) on fouling limitation in submerged membrane modules of a pilot MBR system

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ABSTRACT

In Europe some years ago, there was no knowledge on Membrane Bioreactor (MBR) wastewater treatment (WWT) systems and particularly to relevant WWT plants. However, in the last decade MBR configuration has proven to be optimal for treatment of many municipal and industrial WWT plants when treatment efficiency is an important consideration. The most obvious appeal of the MBR technology is that produces an excellent effluent quality and eliminates the need for good sludge settleability as the basic requirement. Due to compact footprint and great potential for automation it is less sensitive to operations, and enables precise control of the sludge residence time (SRT) and, thus, correspondingly, control of mixed liquor suspended solids (MLSS). This both reduces the required reactor size and promotes the development of specific nitrifying bacteria, thereby enhancing ammonia removal, as well as producing less sludge. However, as with almost all other membrane processes, the production rate of MBRs is ultimately limited by membrane fouling. Fouling probably is the most critical problem of the Submerged Membrane Bioreactors (SMBRs), and the used techniques to avoid this problem have the disadvantage of the high energy needed.

The objective of this study is to introduce an alternative cleaning technique of submerged membranes, with reduced energy consumption. 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). In this study the feasibility of HFPV, as a cleaning technique, on fouled membrane modules, in a small pilot scale submerged MBR (SMBR) system, treating a novel Synthetic Wastewater (SWW), was examined. This pilot scale system comprised from small copies of commercialized filter modules working under low aeration mode, in order to study the membrane fouling in a relatively short time period. Three identical, parallel Hollow Fiber (HF) filter elements were used in the SMBR unit in a comparative study. The object of this comparison was the behavior of the membranes in terms of their operative characteristics, Trans Membrane Pressure (TMP) and Flux, when different types of vibration were applied, versus time.

After working the unit for a long time period, where fouling arises from the accumulation of solute, colloidal, and particulate species on or within the membrane, leading to a deterioration in membrane permeability, various time-period HFPV schemes were applied on the filter modules, via two different in power commercial pneumatic vibrators. These HFPV schemes give specific vibration characteristics (frequency, displacement, acceleration, etc.) to the membrane modules and their effectiveness on filter fouling was monitored continuously via TMP and flux values versus time, without interrupting the operation of the whole SMBR system. This results a considerably lower TMP values while flux was recovered to initial values and the system after that, behaved similar with that of having new filter modules in terms of TMP and flux values.

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 implementation of vibration. In addition this technique copes with the problem of membranes fouling in real-time, by applying HFPV schemes without interrupting the operation of the SMBR system.

Keywords: Membrane bioreactor; MBR; membrane fouling; High Frequency Power Vibration;

1. Introduction

Wastewater treatment processes using MBRs have a variety of advantages over conventional biological processes. Additionally, stricter legislation on effluent disposal, in combination with the decrease in membrane costs affecting the overall operational costs, introduces the treatment process of MBRs, as a globally accepted technique in the last years [1].

Membrane fouling control remains the most critical problem in the successful application and cost-efficient operation of SMBRs, and it is the key for the steady operation of SMBRs [2–4] and one of the most challenging issues facing further MBR development [5-7]. Several necessary strategies are employed in order to reduce membrane fouling nowadays, such as applying appropriate pretreatment to the feed water, employing appropriate physical or chemical cleaning protocols, reducing the flux, increasing the aeration, modifying chemically or biochemically the mixed liquor [1]. All the above mentioned either lead to the increase of operating and maintenance costs or to the oversize the installation. 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 [8]. The use of air bubbles in such a manner to induce flow circulation and shear stress on the membrane surface demonstrated as the most widespread and applied strategy by membrane manufacturers to reduce fouling effect since the first appearance of the SMBR systems [4]. However, air bubbling method has several limitations. The shear forces generated by air-scouring or cross-flow on the membrane surface are relatively weak and not effective in achieving and maintaining high fluxes due to hydrodynamic limitations [9]. Moreover in this process design, the mixed liquor recirculation (MLR) is highly aerated by the membrane air scour system, and the rate of recycling is not set to optimize biological process requirements, but rather is selected to ensure optimum membrane performance. The consequence of these two obstacles in MBR designs is that the downstream of the biological process is highly aerobic and highly mixed so this can lead potentially to releasing ortho-phosphate to the plant effluent [10]. Finally, air-scouring in MBRs has proven to be energy intensive. Dynamic or shear-enhanced filtration, which consists in creating the shear rate at the membrane by a moving part such as a disk rotating near a fixed membrane, or rotating or vibrating membranes, permits to generate very high shear rates without large feed flow rates and pressure drops. This could be a viable alternative to cross-flow filtration [11].

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. [12] 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 [13]. They evaluated the effect of vibration with a frequency of 70 Hz and 19 mm amplitude in a sludge feed with MLSS of 1800 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. [14] 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. [15] 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 [16]. A slight variant of the foregoing technique, investigated by Altaee et al. [9], 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 1.67-6.68 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 of shear force at the membrane-water interface which in turn enhanced the particles back diffusion mechanism. Similarly Bilad et al. [17] created a magnetically induced membrane vibration (MMV) 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 0-60 Hz and amplitude of 2 mm. The vibration 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. [18] 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.

Although all the referred studies reported a significant improvement on both the permeate flux, suction pressure and the sustainability of operation, they face numerous limitations such as, the vibrating system is often restricted to a small range of vibration amplitudes and frequencies [17], due to the lack of anti-vibration devices on the holding system of the membranes; the shear rates were somehow reduced, due to energy loss resulting from the mechanical contacts and their friction [17]; 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 [17]; in most studies, the offered vibration power was limited; in most studies, experiments were performed in a very short time span of few minutes or hours; in some cases, 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); in most cases, it was not used real or simulated waste water as an influent; little research was done to examine the impact on different material and type of membranes; the already examined systems and techniques are not feasible to be used in currently known SMBR modules, especially due to the large vibration amplitude; in some cases, the MLSS concentration was very low; in many cases, experiments were handled without the recommended by the manufacturers membrane relaxation period, that is essential due to the membranes construction material.

The purpose of this work was to introduce a new approach of applying high frequency powerful Vibration (HFPV) in membrane modules via pneumatic vibrators and investigate the impact on the membrane fouling control. The experiments were carried out in a pilot-scale SMBR unit, treating simulated synthetic municipal wastewater operated previously for a period of 230 days giving steady operating conditions for this investigation.

2. Materials and Methods

2.1 Synthetic Wastewater

For the operating needs of the pilot SMBR unit, a new strong, in terms of organic load SWW (COD ~ 700 mg/lt) [19]. Components for preparing the SWW are shown in Table 1. Activated sludge which obtained from a municipal wastewater plant was 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 the final features. The synthesis of SWW supplemented with minerals and trace elements such as K, Fe, Cu, Mn, Zn, Ca, Mg.

Table 1. SWW components

Component	Chemical Formula	Concentration in SWW (mg/L)
D(+)-Glucose	$C_6H_{12}O_6\ H_2O$	400±10
Peptone A	Peptone from soymeal	50±2
Peptone B	Peptone from gelatin	150±5
Urea	$CO(NH_2)_2$	50±2
Ammonium Sulfate	$(NH_4)_2\ SO_4$	50±2
Ammonium chloride	$NH_4\ Cl$	50±2
Potassium dihydrogen phosphate	$KH_2\ PO_4$	15±1

2.2 Membrane module's properties

Specifications of the membrane elements used in the pilot plant are shown in Table 2.

Table 2. Specifications of the membranes

FILTRATION TYPE	MEMBRANE MATERIAL	PORE SIZE (μm)	MEMBRANE AREA (m^2)	TYPE
UF	PVDF	0.1	0.05	HF

Hollow Fiber (HF) membrane elements were small copies of production models prepared from manufacturer for our lab unit.

2.3 MBR pilot system description

The SMBR pilot system has been presented elsewhere [19]. The vibration system consists of the vibration header/s, air compressors, feed air pipes, regulation/control valves, and pressure measurement/control apparatus. A pneumatic ball vibrator header (Fig. 1) is fastened on each of the collector suction lines of the two membrane modules, in order to provide shear forces through powerful vibration [19]. Frequency and centrifugal force can be easily changed only by operating the pressure of compressed air. In the present experimental procedure, two types of pneumatic ball vibrators were used.

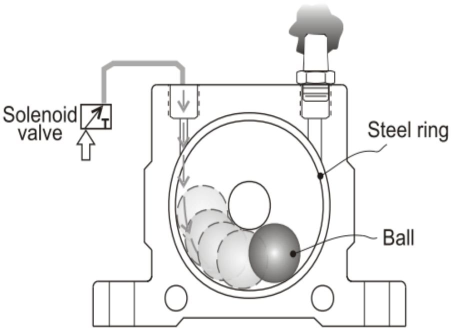

Fig. 1. Pneumatic ball vibrator header scheme

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. In this study, vibration experiments took place during relaxation period of filtering process. The vibration moves the membrane in a powerful way to all directions (Fig. 2). Desired amplitude and 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.

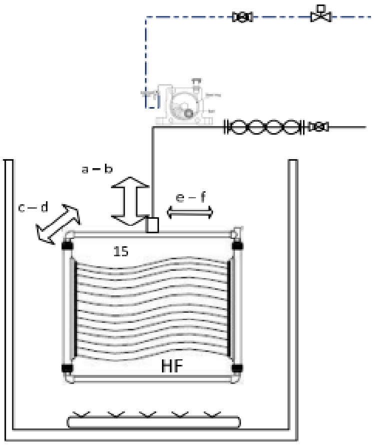

Fig. 2. Schematic overview of the powerful vibration moves of the membrane

2.4 SMBR experimental conditions

The SMBR pilot-scale system was operated for a period of more than 200 days, 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. According to the manufacturer's instructions, the membrane aeration rate for every HF membrane element should be 1.5-2 L/min. Throughout of all the experiments, the system was supplied with 1.5-2 L/min for all the three HF membranes per module, so the air-scouring flow was set to 1/3 of the manufacturer's instructions. Moreover, no backwash cleaning procedure took place in this study. The membrane module's HFPV vibration characteristics, using the K8-K and K16-K vibrator types, were measured with special measuring equipment (Laser Doppler vibrometer) and are shown in Table 3. HFPV vibration characteristics applied to the membranes, using the K8-K and K16-K vibrator types, were measured with special measuring equipment (Laser Doppler vibrometer) are shown in Fig. 3.

Table 3. Membrane module's vibration types and characteristics

Vibrator type	Membrane 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	H.F.	7	4	223	142	20	0.3
K16-K	H.F.	5	3	76	134	6.6	0.78

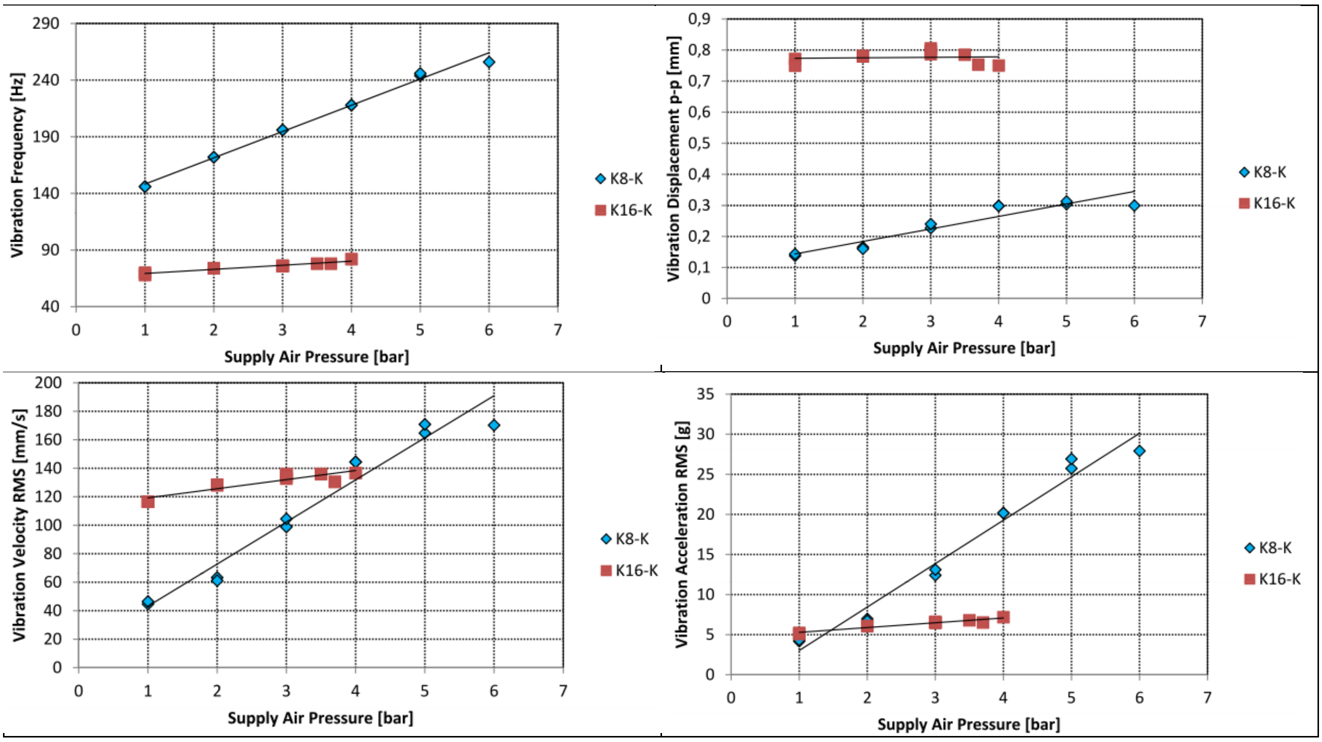

Fig. 3. HFPV vibration characteristics.

3. Results and Discussion

Evaluation of HFPV application on HF membrane module was lasted 28 d (28 d experiment) monitoring the TMP and permeate flux of effluent vs. time. Three identical, new, in a parallel arrangement HF filter elements, were used in the SMBR unit in a comparative study. The object of the comparison was to study the behavior of the membranes in terms of their basic characteristics, (TMP and Flux), when different types of vibration were applied, versus time.

Presented values normalized to a standard temperature of 20°C. Moreover, flux and TMP values were additionally confirmed by measuring manually the effluent volume and by mechanical glycerin gauges, respectively.

In the first phase of the experiment (days 1 to 14) the first membrane (A1) works as a reference membrane (Fig. 4). The same can be said also for the third membrane (A3) for these days (see fig. 7) because until then no vibration has been applied. Comparing fig. 5 & 7 we observe that the two membranes (A1) and (A3) have the same behavior over the time, while (A1) presenting a little worse behavior, probably because it is closer to the MBR tank surface, where air scouring conditions might be lower. Implementation of vibration was decided when the characteristics of the process deteriorated significantly.

Three different vibrating types were applied in this experiment as follows:

a) type 1 (V.T. 1) - vibration implementation with a K8-K vibrator working under air pressure of 4 bar for 5 minutes,

b) type 2 (V.T. 2) - vibration implementation with a K16-K vibrator working under air pressure of 3 bar for 5 minutes,

c) type 3 (V.T. 5) - vibration implementation with a K8-K vibrator working under air pressure of 4 bar for 10 minutes.

Fig. 5 shows the recorded TMP and permeate flux data vs. time for the second membrane (A2). This diagram shows a significantly faster reduction in the flux of this membrane element, to about 8L/m^{2}h i.e. 1/3 of the initial flux, within six days (day 6). Under these conditions it was decided to apply a V.T. 2 vibration to the membrane. After the vibration implementation, according to Fig. 6 appears that the flux of the membrane almost doubled after reaching 14.7 L/m^{2}h, while the TMP value was reduced significantly from 110 mbar to 58 mbar i.e. approximately half. The above procedure allowed continuing the comparative testing of the three membranes since the progress of the TMP thereafter was smooth and the slope of the flux reduction improved significantly.

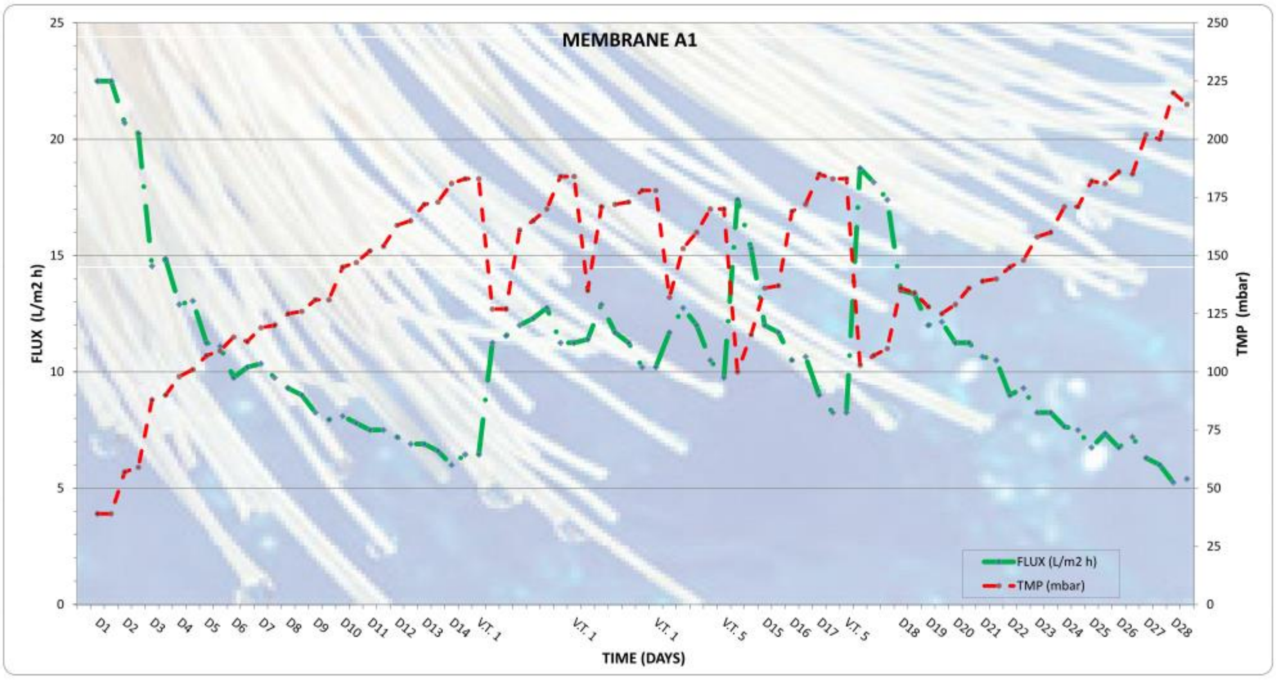

Fig. 4. TMP and permeate flux profiles vs. time on A1 HF membrane.

In the following eight days till day 14 the experiment ran smoothly for all three membranes. On day 14, according to Fig.1 & 3, flux mainly of A1 and A3 membrane decreased significantly to 6L/m^{2}h (low set value) and 7.65 L/m^{2}h respectively while the TMP values of all three membranes reached almost 180 mbar (183/184/175 mbar). For similarity and comparison reasons between different types of vibration, it was decided to apply vibration almost simultaneously to the tree membranes.

In membrane A1 vibration type 1 (V.T.1) was applied whereas in membranes A2 and A3 vibration type 2 (V.T.1) was applied.

Fig. 4 shows operation characteristics of A1 membrane vs. time in the second phase of the experiment, (after day 14) under V.T.1 implementation. The HFPV implementation was started during day 14, and was repeated three times, as depicted in Fig. 5, 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 L/m^{2}h to 12.75 L/m^{2}h, while the TMP value was reduced significantly from 183 mbar to 127 mbar. After the second and third implementation of V.T.1, a less positive contribution effect to the above parameters was observed, after the implementation of which, the characteristics of the membrane were restored 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 (V.T.5) in order to examine the behaviour of the two different types of vibration.

V.T.5 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 initial levels (180 mbar). The experiment was repeated on day 17 with better results as shown to Fig. 5.

Fig. 5 shows operation characteristics of A2 membrane vs. time in the second phase of the experiment, (after day 14) under V.T.2 implementation as prior mentioned. The second V.T.2 implementation on A2 membrane increased the flux from 11.55 L/m^{2}h to 19.35 L/m^{2}h, while the TMP value was reduced significantly from 184 mbar to 54 mbar i.e. less than 1/3 of the initial TMP. The second V.T.2 implementation took place on day 18 followed the V.T.1 on A1 membrane for comparison reasons, although there was no need for that. After that, operation characteristics were recorded until reached high or low values for TMP and flux respectively. In the following ten days according to fig. 6 TMP reached 200 mbar and flux fell to 7.5 L/m^{2}h.

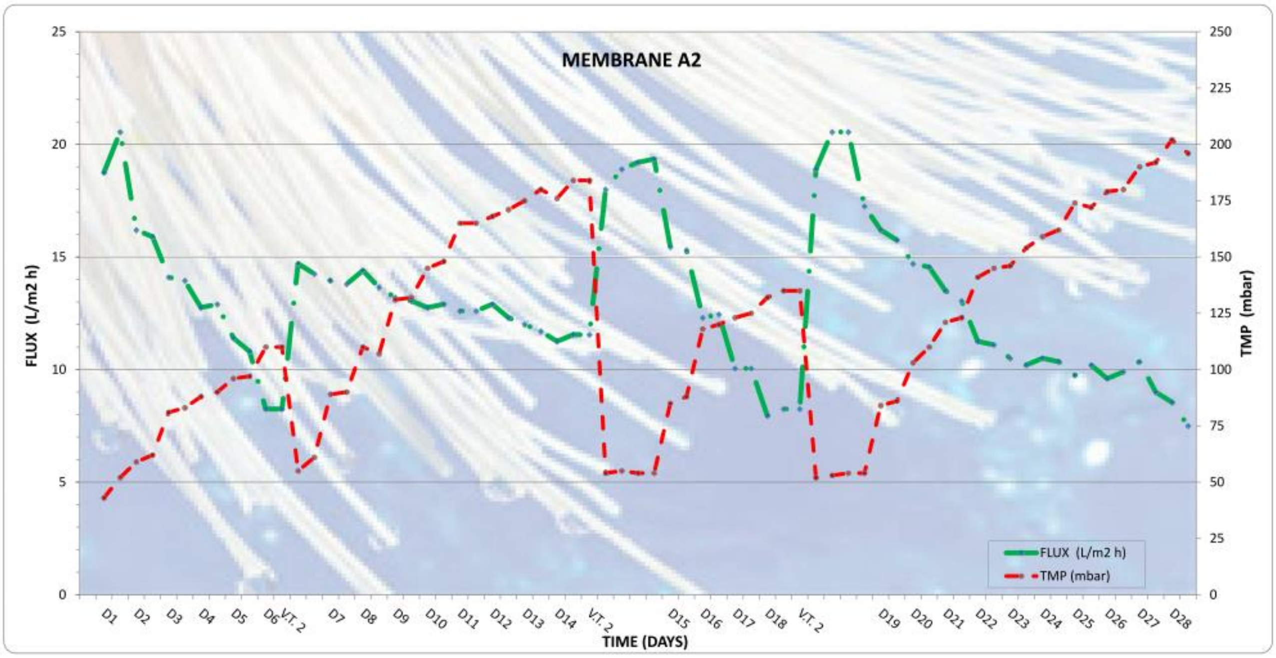

Fig. 5. TMP and permeate flux profiles vs. time on A2 HF membrane module.

In Fig. 6 operation characteristics of A3 membrane vs. time were presented in the second phase of the experiment, (after day 14) under V.T.2 implementation. The first V.T.2 implementation on A3 membrane increased the flux from 7.65 L/m^{2}h to 20.7 L/m^{2}h i.e. almost three times up, while the TMP value was reduced significantly from 175 mbar to 48 mbar i.e. less than 1/3 of the initial TMP. The second V.T.2 implementation took place on day 18 followed the V.T.1 on A1 membrane and V.T.2 on A2 membrane, for comparison reasons, although there was no significant need for that. After that, operation characteristics were recorded until reached high or low values for TMP and flux respectively. In the following ten days according to fig. 7 TMP reached 182 mbar and flux fell to 7.8 L/m^{2}h.

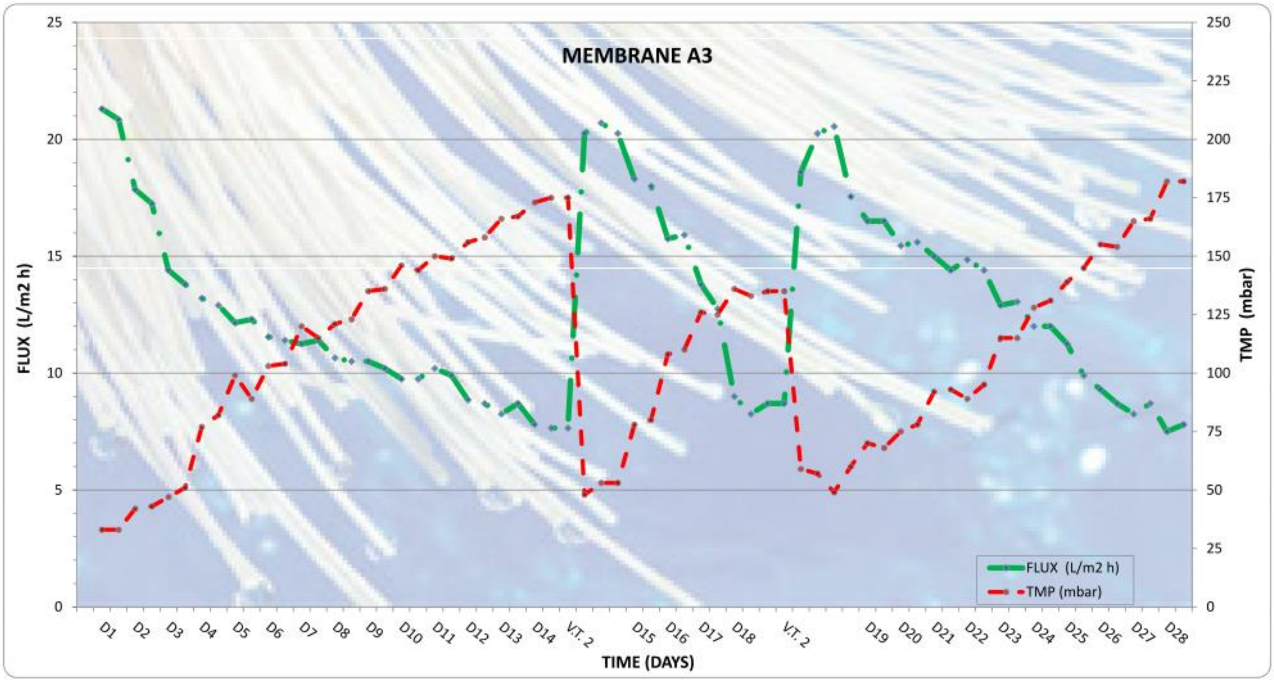

Fig. 6. TMP and permeate flux profiles vs. time on A3 HF membrane module.

4. Conclusions

The HFPV technique applied in this study on membrane modules in a small pilot-scale SMBR system treating Synthetic Waste Water was found to be very promising. The results showed clear advantages of this vibrating technique over the air-scouring conventional MBRs cleaning processes, in terms of realizable flux and membrane fouling control. The performance of the HFPV technique applied on HF membranes seems to be very high, returning the behaviour of the fouled membranes almost to the cleaned ones, in terms of TMP and flux measuring values.

Comparison between implementation of the same vibration type (V.T.2) on the same membrane type with similar fouling condition gives almost identical features confirming that the method is appropriate. At about the same conclusion we arrive and by repeating the vibration V.T.1 on the A1 membrane. When applied elongated vibration time from 5 minutes of V.T.1 to 10 minutes of V.T.5 different results recorded. It is observed that the elongation of the vibration time affects the results positively.

The repeated vibrations in all of three 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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