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Investigation of module vibration in ultrafiltration

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ABSTRACT

Membrane fouling is still a critical issue which limits the application of industrial membrane utilizations. Membrane processes operating at a high shear rate are frequently used to control flux decline by reducing the deposition of particles on the membrane surface. In this work, ultrafiltration (UF) of a dairy model and industrial wastewaters was investigated. Membrane module vibration and no-vibration mode were compared by a laboratory mode vibratory shear enhanced processing device during membrane filtration with the same operational parameters. Membrane fluxes, rejections, and energy consumption were measured and calculated for comparison of the vibration effectiveness. Turbidity, chemical oxygen demand, and total organic carbon were measured. The UF experiments were carried out with constant parameters at a temperature of 50°C and recirculation flow rate of 910 L h^{-1} at 0.8 MPa. Furthermore, to understand the fouling mechanisms in depth, contact angles of the clean, prewetted, and fouled membrane were measured to determine the wettability for characterization of the membrane.

Keywords: Ultrafiltration; VSEP; Membrane module vibration; Dairy wastewater; Contact angle

1. Introduction

Increasing population and industrialization have considerably increased large-scale water quality degradation and water pollution. More stringent European regulations and threshold limits have been imposed to protect and conserve the environment [1]. Food industries, such as the dairy industry, require and generate huge volumes of water and wastewater and have wide fluctuations in their effluent quality [2]. In dairy industry technology, water is used throughout all steps including cleaning, sanitization, heating, cooling, and floor washing, generating large volumes of effluents, mainly white waters. On the one hand, dairy wastewater has high biochemical oxygen demand and chemical oxygen demand (COD) contents, high levels of dissolved or suspended solids including fats, oils, and grease, nutrients such as ammonia or minerals and phosphates, milk components like lactose and proteins, and cleaning chemicals and detergents, and therefore it requires proper attention before disposal [3]. On the other hand, this effluent may result in

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water eutrophication due to the presence of nitrogen and phosphorus when it is discarded without treatment [4,5]. For this reason, treating dairy effluents is one of the most crucial tasks not only for the environment, but also for water recycling. A number of different processes, like biological and physico-chemical methods, have been used to treat dairy wastewaters effectively, such as the activated sludge process [6], trickling filter and anaerobic sludge blanket reactors [7], anaerobic filters [8], adsorption [9], and ion-exchange techniques [10]. However, each of the mentioned methods has its own disadvantages caused by serious operational difficulties, high running costs, large land requirements, or excessive installations [11]. Membrane technologies are promising methods to treat dairy wastewaters. For this reason some works have focused on the treatment of dairy effluents by nanofiltration (NF) and reverse osmosis (RO) [3,12]. The main disadvantage of membrane filtration in dairy wastewater treatment is membrane fouling, which causes flux decline, decreased membrane lifetime, and increased operational cost. According to some earlier reports, the use of vibratory shear enhanced processing (VSEP) systems could efficiently prevent fouling in various wastewater treatments by producing a high shear rate on the surface of the membrane without a pressure drop [13–15]. The very few works which have been dedicated to the treatment of dairy wastewater by VSEP show that NF or RO is adequate for the concentration of milk components [14,16]. Furthermore, the number of works on dairy effluent purification by VSEP ultrafiltration (UF) is very limited [17–19].

In this study, the performances of a VSEP system for UF of model and industrial dairy wastewaters and the effects of pressure and vibration oscillatory frequency on the membrane separation efficiencies were investigated. Furthermore, the energy consumption was measured and calculated for comparison of the vibration effectiveness. To understand the fouling mechanisms in depth, the contact angles of the clean, prewetted, and fouled membrane were also compared and some scanning electron microscopy (SEM) pictures were taken.

2. Materials and methods

2.1. Feed dairy wastewater

Model dairy wastewater was prepared from skimmed milk powder (2.5 g dm^{-3}) (Szekszárd, Tolnatej Zrt., Hungary) and the anionic surfactant cleaning agent Chemipur CL80 (Nagycserkesz, Hungaro Chemicals, Hungary) at a concentration of 0.5 g dm^{-3}. The industrial dairy wastewater was provided by Sole-Mizo Ltd (Szeged, Hungary). The wastewater characteristics are given in Table 1.

2.2. Analytical methods

The turbidity of the samples was determined with a HACH2100N turbidimeter (Hach, Germany). The COD was analysed in test tubes with an ET 108 digester and a PC CheckIt photometer (Lovibond, Germany). The total organic carbon (TOC) content measurements were carried out with an advanced TOC analyzer (Teledyne Tekmar Torch, USA). Three repeated COD and TOC measurements were taken for each sample, and the average value was reported.

2.3. VSEP experimental setup

A VSEP Series L membrane device equipped with a single circular UF membrane of 503 cm^2 with an outer radius (R_2) of 13.5 cm and inner radius (R_1) of 4.7 cm was used for the UF experiments (New Logic Research Inc., USA), as shown in Fig. 1. Supporting the membrane housing is a vertical shaft, which acts as a torsion spring and transmits the oscillations of a lower plate in the base which is vibrated by an eccentric drive motor. As a result, the housing containing the membrane oscillates azimuthally with a displacement amplitude (d), which we have adjusted to be 2.54 cm (1 inch) on the outer rim at the resonant frequency of 54.2 Hz (F). The mean and the maximum shear rates, which vary sinusoidally with time and proportionally to the radius, were calculated in Akoum et al. [20] to be:

$$\gamma_w = \frac{2^{3/2}(R_2^3 - R_1^3)}{3\pi R_2(R_2^2 - R_1^2)}\gamma_{w\,\max} \quad (1)$$

$$\gamma_{w\,\max} = 2^{1/2} d(\pi F)^{3/2} v^{-1/2} \quad (2)$$

where γ_w is the mean shear rate [s^{-1}], $\gamma_{w\max}$ is the maximum shear rate [s^{-1}], R_1 is the membrane inner radius [m], R_2 is the membrane outer radius [m], F is the vibration oscillatory frequency [Hz], d is the membrane displacement at the periphery [m], and v is the fluid kinematic viscosity [$m^2 s^{-1}$]. The shear rates are shown in Fig. 2. Table 2 shows the UF membrane characteristics.

2.4. Membrane separation tests protocol

The measurements of VSEP were carried out at 50 ± 1 °C, as this is an average temperature value for the

Table 1
Dairy wastewater (ww) parameters

	Turbidity [NTU]	COD [mg L^{-1}]	TOC [ppm]	Viscosity [mPas]	Conductivity [mS cm^{-1}]	pH [–]
Model ww	250	3,880	350	1.18	0.99	7.29
Industrial ww	582	3,660	505	1.26	1.32	8.14

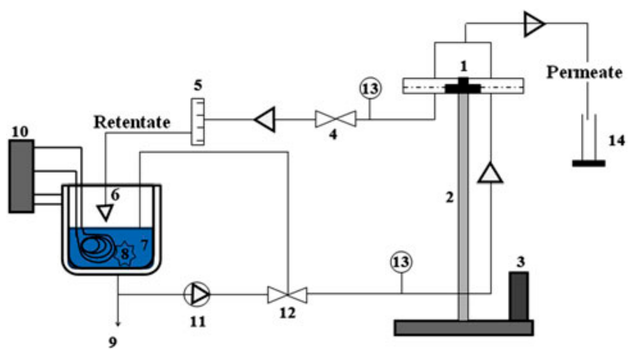


Fig. 1. Schematic diagram of VSEP system: (1) membrane module; (2) torsion spring; (3) vibration eccentric motor; (4) valve 1; (5) flow meter; (6) thermostated feed tank; (7) wastewater; (8) thermometer; (9) bibcock; (10) thermostated puffer tank; (11) feed pump; (12) valve 2; (13) pressure transducers; (14) permeate.

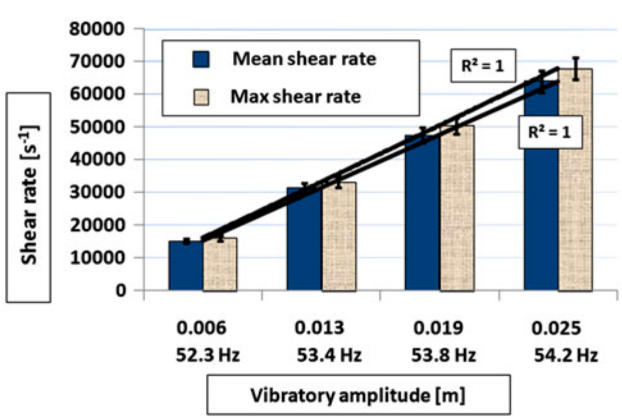


Fig. 2. The mean and maximum shear rate changing as a function of vibratory amplitude and vibration oscillatory frequency.

homogenized dairy wastewaters produced in the industry, and the recirculation flow rate (q_V) was constant at a high value of 910 L h^{-1}. Before measuring the membrane hydraulic permeability with deionized water, prefiltration was carried out for 60 min at the tested parameters (temperature, recirculation flow rate, transmembrane pressure [TMP]) to ensure membrane stabilization. Afterward, the feed tank was filled with wastewater, the feed pump was started, and the vibration amplitude was adjusted by increasing the frequency, if the vibration mode was used. When the desired parameters had been reached and had stabilized, the wastewater permeate flux was measured and samples were collected. In order to investigate the TMP-flux profiles to see the effects of pressure, TMP stepping experiments were carried out in the first part of this study. In these experiments the permeate was collected and then measured by analytic methods (turbidity, COD, and TOC). In the other part of the experimental work, in order to find out the effects of the vibration oscillatory frequency, the permeate was recycled back to the feed tank continuously, but a volume of 30 mL was separated for sampling every 225 s. (3.75 min).

2.5. SEM pictures

SEM was carried out on a Hitachi S-4700 field emission SEM instrument operated at an acceleration voltage of 7 kV in ultrahigh resolution mode. To analyse the UF membrane, 50- and 250-fold magnification pictures were taken and compared.

2.6. Contact angle measurements

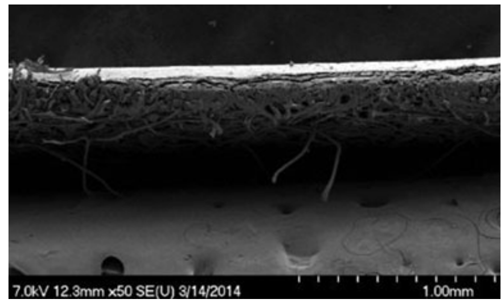
The clean, fouled, and prewetted UF membrane hydrophilicity was quantified and compared by measuring the water contact angle that was formed between the membrane surface and deionized water. Water contact angles were measured at 25˚C and 50% RH on a contact angle system (OCA 15Pro, Dataphysics Instruments, Germany). Then, 10 μL of deionized water was dropped on the top surface and the dynamic contact angles were determined immediately. To minimize the experimental error, the contact angle was measured at four random locations of the membrane and three times for each sample and then the average value was reported.

3. Results and discussion

3.1. Effects of TMP

Analysis of the flux variations with TMP, as shown in Fig. 3(a), where UF was carried out with model dairy wastewater, and in Fig. 4, where industrial dairy

Table 2
Membrane characteristics

Membrane brand name	PES-10 SYN	
Pore size, MWCO [Da]	10.000	
Membrane material	Polyethersulfone	
Vendor	Synder	
pH tol.	2–12	
Temp. tol. [℃]	90	The clean UF PES membrane PES-10 SYN (50× cross-section)

wastewater was used as a feed wastewater, were carried out. In Fig. 3(a), variations of permeate fluxes during TMP stepping from 0.3 to 0.8 MPa and back are indicated. As shown in Fig. 3(a), the permeate flux increased almost linearly with TMP from 0.3 to 0.8 MPa, indicating that a significant cake layer did not form at the high shear rate of 54.2 Hz vibration oscillatory frequency. Only a small flux decline occurred between the same TMPs, in other words the fluxes became almost stable, indicating that 0.8 MPa did not surpass the threshold flux and did not result in high membrane fouling. Furthermore, from our membrane rejection experiments, we can conclude that the turbidity rejections were always higher than 98.6%. This was also confirmed by the direct observations, as all samples looked visually very clear. However, the COD rejection changed as a function of pressure, showing a tendency to increase slightly from 72 to 81% at TMPs of 0.3 and 0.8 MPa, respectively, and then decreasing back to 72% (Fig. 3(b)).

To analyse the flux variations with TMP in more depth, UF was carried out with deionized water and dairy industrial wastewater in vibration and no-vibration modes, and the results are represented in Fig. 4. The fluxes of deionized water and wastewater using vibration mode with 54.2 Hz frequency had linearly

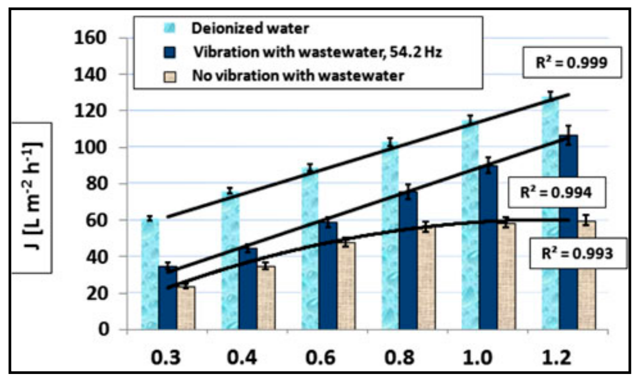


Fig. 4. Variation of industrial wastewater permeate fluxes with TMP ($T = 50 \pm 1$℃; $q_V = 910$ L h^{-1}).

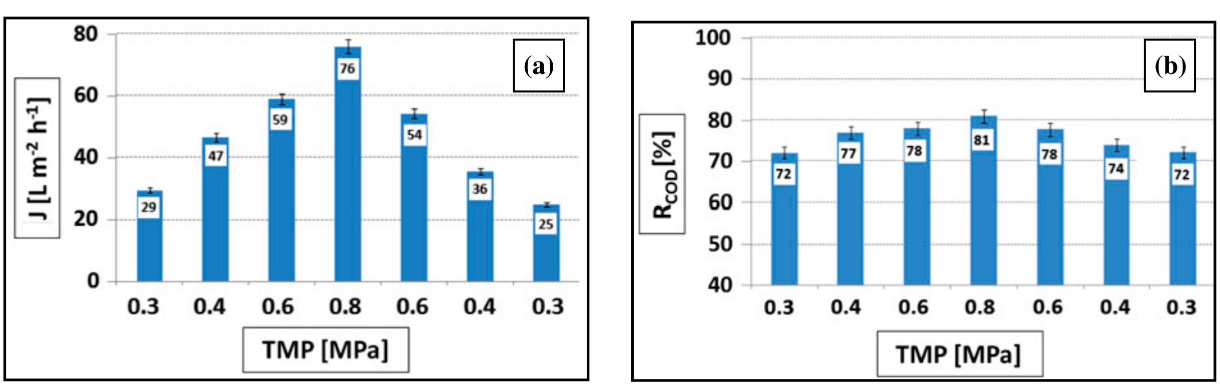


Fig. 3. Variation of model wastewater permeate fluxes (a) and COD rejections (b) with TMP ($T = 50 \pm 1$℃; $q_V = 910$ L h^{-1}; $F = 54.2$ Hz).

increasing tendencies as the TMP was progressively raised. However, in the case of no vibration, a stabilized flux was observed at 0.8 MPa. This means that the vibration mode flux became independent of TMP above this pressure. This clearly identified a flux value in our case, which is the threshold flux. Luo et al. introduced some flux definitions related to the critical flux family [15]. They clarified that at or below the threshold flux the polarized layer is dynamic and the rejected particles on the membrane surface create a constant filtration resistance, while above this threshold flux the deposited and accumulated particles cause higher resistances. For this reason a TMP of 0.8 MPa was used in each further experiment.

With regard to the quality of the permeate, Fig. 5 shows the UF membrane COD and TOC rejections. It was observed that the permeate COD quality depended non-significantly upon the TMP. On the one hand, the vibration mode increased the membrane rejection slightly in all cases. On the other hand, the COD rejections also slightly increased from 75 to 80% in no-vibration mode and 77–81% in vibration mode when TMP increased from 0.4 to 1.2 MPa. Increases in TMP also led to increases in TOC rejections from 52 to 63% in no-vibration mode and from 63 to 65% in vibration mode. However, these TOC differences were not significant, but the flux increases were more emphasized using vibration mode compared to no-vibration mode (Fig. 4). The increase of TMP does not affect the shear rate on the membrane surface but it might change the cake layer compatibility and structure.

3.2. Effects of vibration oscillatory frequency

Variations of permeate flux with increases in oscillation frequency are shown in Fig. 6. Each frequency step lasted only 30 min (1,800 s) from no vibration ($F = 0$ Hz to 54.2 Hz) frequency vibration, which was the maximum usable frequency value of the device from a long-term point of view using the examined feed. The increase in the vibration oscillatory frequency induces higher shear rates on the membrane surface and thus enhances the permeate flux. As can be seen in Fig. 6, an increase in maximum flux (44%) was observed at 54.2 Hz vibration compared to the no-vibration mode. The increases in flux were calculated from the average permeate flux of each 30 min experiment and compared to the average flux of the no-vibration mode experiment (45.2 $\mathrm{L m^{-2} h^{-1}}$). From these experiments we can conclude that the vibration significantly increased the permeate fluxes, even if the rejection values did not increase so much.

Next to the importance of the flux, it is also important to know the specific energy consumption produced per cubic metre of permeate [$\mathrm{kWh\,m^{-3}}$]. Fig. 7 shows the specific energy consumption (E), the energy consumed by the VSEP, during UF experiments in no-vibration and vibration modes with various vibration oscillatory frequencies calculating according to Eq. (3):

$$E = \frac{P_{VM}\,\eta_{VM} + P_{EP}\,\eta_{FP}}{AJ} \tag{3}$$

where P_{VM} is the power consumption of the vibration motor [kW], P_{FP} is the power consumption of the feed pump [kW], η is the efficiency of the pumps [–], and A is the filtration area of the membrane surface [$\mathrm{m^2}$].

The increase of vibration oscillatory frequency induces higher shear rates on the membrane surface but has higher energy demand. In Fig. 7 the specific

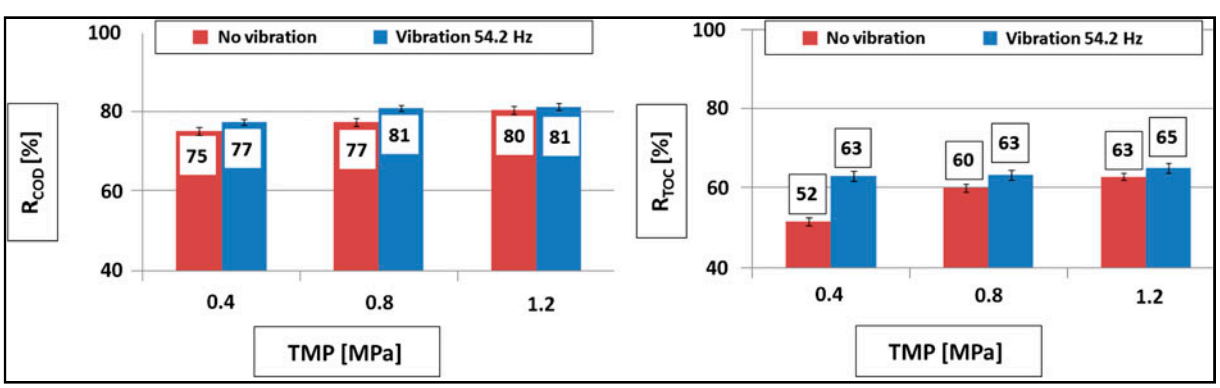


Fig. 5. Variation of industrial wastewater permeate COD (a) and TOC rejections (b) with TMP ($T = 50 \pm 1$°C; $q_V = 910\ \mathrm{L\,h^{-1}}$).

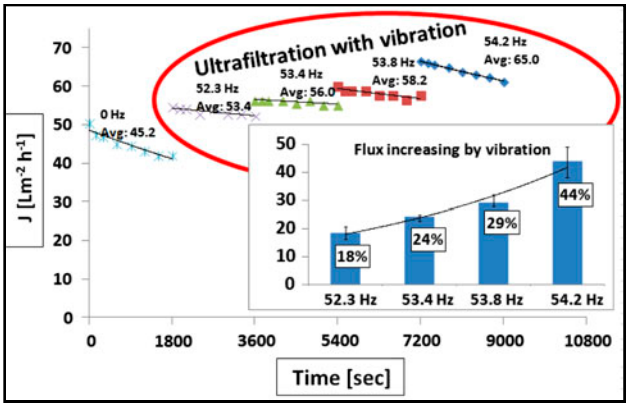


Fig. 6. Variation of permeate fluxes with experimental time (TMP = 0.8 MPa; $T = 50 \pm 1$°C; $q_V = 910$ L h^{-1}).

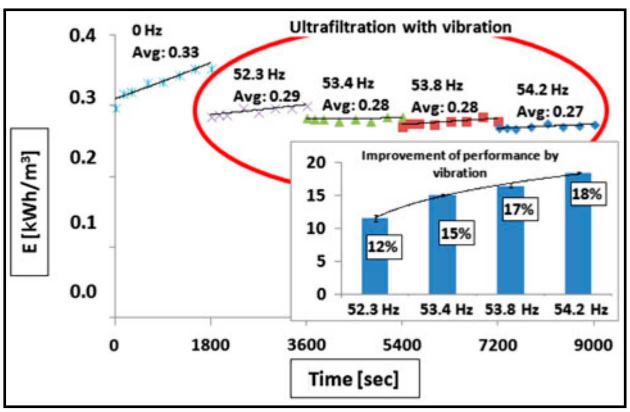


Fig. 7. Variation of specific energy consumption with experimental time as a function of vibration oscillatory frequency (TMP = 0.8 MPa; $T = 50 \pm 1$°C; $q_V = 910$ L h^{-1}).

energy consumption per cubic metre of permeate, which was calculated from Eq. (3), is shown. A decrease in maximum energy demand (18%) was

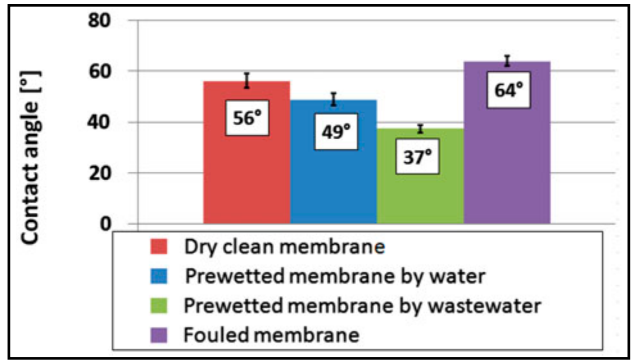


Fig. 8. Variation of contact angle of various pretreated membranes.

observed at 54.2 Hz vibration compared to the no-vibration mode. The values of decreasing energy demand were calculated from the average specific energy consumption of each 30 min experiment and compared to the no-vibration mode (0.33 kWh m^{-3}).

3.3. Effects of membrane prewetting

To understand the wettability of various pretreated membranes by contact angle measurements, clean dry membranes, membranes prewetted by deionized water, membranes prewetted by dairy-industry wastewater, and fouled dry membranes were measured. As shown in Fig. 8, the contact angle of the clean membrane was 56° and decreased to 49° and 37° when membranes were submerged (overnight) in water and wastewater, respectively. This means that the prewetting process made the membrane surface more hydrophilic. However the fouled membrane had a bigger contact angle of 64°, since the forming cake layer resulted in a less hydrophilic membrane surface. In Fig. 9 the SEM pictures of the fouled UF membrane are shown with 50 and 250× magnification.

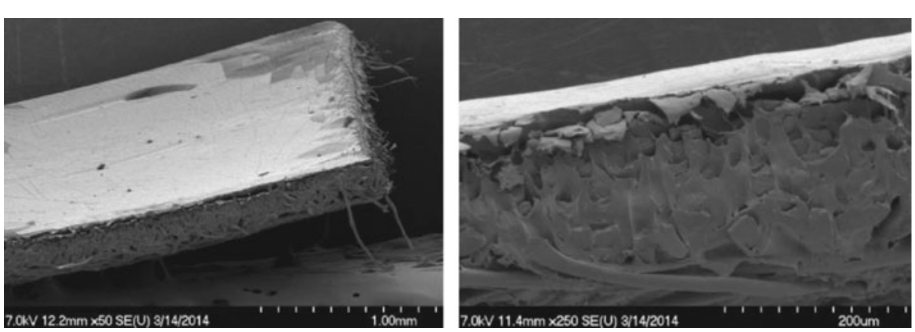


Fig. 9. Fouled PES UF membrane SEM pictures (50× and 250× magnification).

4. Conclusions

This study was focused on the purification of the dairy model and industrial wastewaters by VSEP system by UF. Membrane module vibration and no-vibration mode were compared during membrane filtration with the same operational parameters. Shear enhanced UF membrane filtration had higher fluxes. The vibration permeate flux can increase with TMP until a very high pressure, but the fluxes of the no-vibration mode rise linearly with TMP until 0.8 MPa. This pressure resulted in the threshold flux, which was proposed to distinguish between low and high fouling rates.

From our experiments we can conclude that the membrane module vibration significantly increased the permeate fluxes, even if the rejection values did not increase so much. One of the main advantages of this technology is that it appears to result in a lower specific energy consumption per cubic metre of wastewater permeate, with a larger energy saving.

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