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Effects of shear rate on membrane filtration

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ABSTRACT

Appropriate and advanced wastewater treatment is necessary to effectively decrease the organic load of dairy wastewater before disposal. Despite the advantages of membrane filtration, membrane fouling is still a critical issue which limits the application of industrial membrane utilizations. For this reason increasing the shear rate on the membrane surface is frequently used to reduce the deposition of particles. Currently, limited data is available from previous studies on the application of vibratory shear enhanced processing (VSEP) for dairy wastewater treatment. In this work the feasibility of the purification of dairy wastewater was investigated by a laboratory mode VSEP. Ultrafiltration (UF) and nanofiltration (NF) membranes were tested using both vibration and non-vibration processes with the same parameters. In order to investigate the effects of shear rate, firstly, the influences of the recirculation flow rate of the feed solution on the membrane filtration performance were analyzed. Secondly, to understand the membrane fouling mechanisms in depth, the shear rates on the surface of the membrane were calculated and investigated during vibration and non-vibration process. Finally, UF and NF rejections, based on chemical oxygen demand (COD), conductivity, protein, lactose and dry matter content, and the calculated specific energy consumptions were compared also during both UF and NF separation experiments.

Keywords: Ultrafiltration; Nanofiltration; VSEP; Dairy wastewater; Shear rate; Membrane fouling

1. Introduction

Population growth has considerably increased the degradation of water quality, and water pollution. The more stringent European regulations, as well as improving food safety and trade security have been imposed to protect human health and conserve the environment [1,2]. Food industries, such as the dairy industry, require huge volumes of water and generate high volume wastewaters having wide fluctuations in their effluent quality [3,4]. In the technology of dairy industry, water is used throughout all steps including the washing of equipment, containers and floor, sanitization, heating, and cooling, generating white waters, effluents. Generally dairy wastewaters have high organic content, in terms of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) contents, high levels of dissolved or suspended components including fats, oils, and nutrients such as ammonia or minerals and phosphates, milk components like lactose and proteins. Some constituents are heavy metals, cleaning chemicals and detergents, which require proper attention before disposal [4]. Furthermore, this effluent may result in water eutrophication due to the presence of nitrogen and phosphorus [5]. In order to remove most of the problematic constituents and treat dairy wastewaters effectively a number of different processes, like biological and physico-chemical methods, the activated

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sludge process [6], trickling filter and anaerobic sludge blanket (UASB) reactors [7], anaerobic filters [8], adsorption [9], and ion-exchange techniques [10] have been applied. All of the mentioned methods have limited application due to their own disadvantages caused by serious operational difficulties or high running costs [11]. Membrane processes have been extensively used in food industry and are promising methods to treat dairy wastewaters [12]. Among membrane technologies especially nanofiltration (NF) and reverse osmosis (RO) has been often considered as a promising method to decrease the organic load [10,13]. However ultrafiltration (UF) also could be an effective method, due to it yields a high permeate flux at low transmembrane pressure (TMP), but its permeate quality is too low for the discharge threshold limits [14,15]. A two-stage UF/NF process was proposed for the treatment of dairy wastewater aiming at realize protein concentration in the first stage of UF, and lactose concentration and reusable water production in the second NF stage, with focus on the selection of UF and NF membranes by Luo et al. [16]. In this work they found that, this two-stage UF/NF process had a higher efficiency and less membrane fouling compared to the single NF process. It seems to be an efficient process to combine membranes from microfiltration to reverse osmosis, but the main obstacle of the wider application of membrane filtration processes is the membrane fouling, which causes flux decline, decreased membrane lifetime, and increased operational costs. According to Akoum et al. earlier results, 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 [14–15,17]. The UF and NF treatment of dairy wastewater by VSEP has been investigated by some authors [14–16], but the detailed energy consumptions of the processes has not been investigated yet.

In this study, the feasibility of the purification of dairy wastewater was investigated by a laboratory mode VSEP. The influences of the recirculation flow rate of the feed solution on the UF and NF performance were analyzed. To understand the membrane module hydrodynamics on fouling mechanisms in depth, the shear rates on the surface of the membrane were calculated and investigated during vibration and non-vibration processes. Furthermore, the energy consumption was measured and calculated for comparison of the vibration effectiveness.

2. Materials and methods

2.1. Feed dairy wastewater

Model dairy wastewater (ww.) was prepared from skimmed milk powder (ww. concentration of 5 g dm^{-3}) (InstantPack, Hungary) and the anionic surfactant cleaning agent Chemipur CL80 (ww. concentration of 0.5 g dm^{-3}) (Hungaro Chemicals, Hungary). The model dairy wastewater characteristics are given in Table 1.

2.2. Analytical methods

The turbidity of the samples was determined with a HACH2100AN turbidimeter (Hach, Germany). The electric conductivity and pH were measured with a BVBA C5010 type multimeter (Consort, Belgium). The samples were tested closed reflux method for COD analysis with an ET 108 digester and a PC CheckIt photometer (Lovibond, Germany). The lactose and dry content of the samples was measured by a Bentley 150 Infrared milk analyser (Bentley Instruments, USA). The protein and nitrogen contents of the samples were determined by the Kjeldahl method (Foss, Denmark).

The viscosity and density of the samples were measured by using a vibration viscometer (AND SV-10, Japan) and a portable density meter (Mettler-Toledo Densito 30PX, Switzerland). All of the analytical measurements were repeated three times to calculate an accurate average.

Table 1
Dairy wastewater parameters at 50°C

Model	ww.
Turbidity, [NTU]	325
COD, [mg L^{-1}]	5100
Protein, [g/g]	0.32
Cond., [mS cm^{-1}]	1.3
Viscosity, [mPas]	0.37
Density, [kg m^{-3}]	983.9
pH	7.29

2.3. VSEP experimental setup

The VSEP LP Series membrane device equipped with a single circular 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 and NF filtration experiments (New Logic Research Inc., USA). 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 shown in Fig. 1. As a result, the housing containing the membrane oscillates azimuthally with a displacement amplitude (d), which was adjusted to be 2.54 cm (1 in) on the outer rim at the resonant frequency

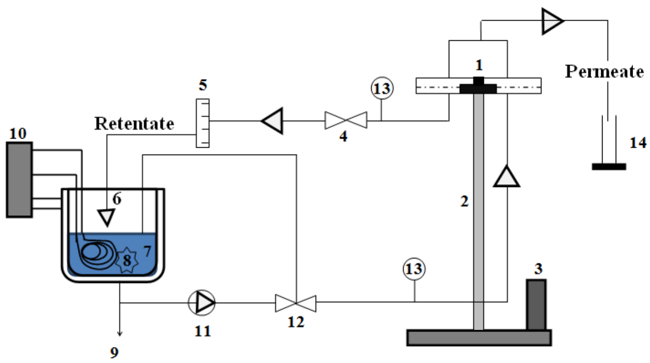

Fig. 1. Schematic diagram of VSEP system: (1) membrane module; (2) torsion spring; (3) vibration eccentric motor; (4) valve 1; (5) flow meter; (6) thermostated feed tank; (7) wastewater; (8) thermometer; (9) bibcock; (10) thermostated buffer tank; (11) feed pump; (12) valve 2; (13) pressure transducers;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

is 54.1 Hz (*F*). The mean and the maximum shear rates, which vary sinusoidally with time and proportionally to the radius, were calculated in Ref. [15] to be:

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

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

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 ν is the fluid kinematic viscosity [$m^2\ s^{-1}$].

Table 2 shows the UF and NF membrane characteristics. Polyethersulfone (PES) 10 kDa ultrafiltration and thin film composite (TFC) 240 Da nanofiltration membranes were purchased. All of the membranes were washed then soaked in deionized water for 24 h prior to use.

2.4. Membrane separation tests protocol

The measurements of VSEP were carried out at 50 ± 1°C. For each experiment a new membrane was used. 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) to ensure membrane stabilization. In order to investigate the transmembrane pressure–energy consumption profiles to see the effects of pressure, TMP stepping experiments were carried out in the first part of this study. 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 the other part of the experimental work, in order to find out the effect of the shear rate on the flux values, energy consumption and membrane rejection separation experiments were carried out with 4 and 16 dm 3 min^{-1} of recirculation flow rate using vibration and non-vibration modes.

2.4.1. Transmembrane pressure (TMP) stepping experiments

TMP stepping experiments were carried out with 10 L of deionized water to select the best filtration condition of TMP related to specific energy consumption.

2.4.2. Separation experiments

In separation tests, 10 L of feed model wastewater was ultra- or nanofiltered to a retentate volume of 2 L (to volume reduction ratio, VRR = 5).

2.5. Calculated parameters

The permeate flux, *J* [$m^3\,m^{-2}\,s^{-1}$] was defined using Eq. (3).

$$J = \frac{dV_p}{d\tau}\times\frac{1}{A_m} \quad (3)$$

where V_p is the volume of permeate [m^3], τ is the membrane filtration time [s] and A_m is the effective membrane area [m^2].

The specific energy consumption, *E* [kWh m^{-3}] was calculated by the following equations:

$$E_v = \frac{\eta_{fp}\times P_{fp} + \eta_v \times P_v}{J\times A_m} \quad (4)$$

$$E_{vn} = \frac{\eta_{fp}\times P_{fp}}{J\times A_m} \quad (5)$$

where E_v is the specific energy consumption produced per cubic meter of permeate with vibration mode and E_{vn} is the specific energy consumption produced per cubic meter of permeate with non-vibration mode [kWh m^{-3}]. *PVM* is the power consumption of the vibration motor [kW], *PFP* is the power consumption of the feed pump [kW] and η is the efficiency of the pumps [–].

The selectivity of the membrane, *R* [%], for a given solute was expressed by the average retention:

$$R = \left(1 - \frac{c}{c_0}\right)100 \quad (6)$$

where *c* is the average concentration of the solute in the permeate phase, and c_0 is the concentration of the solute in the bulk solution.

Reynolds number was calculated using Eq. (7).

$$Re = \frac{d\times v\times\rho}{\eta} \quad (7)$$

where *d* is the equivalent diameter of the module [m], *v* is the wastewater velocity in the membrane module [m s^{-1}] and ρ is the density [kg m^{-3}] and η is the dynamic viscosity of the feed wastewater [Pas].

In vibration mode the mean and the maximum shear rates were calculated using Eqs. (1) and (2). The shear rates,

Table 2
Membrane characteristics

Membrane		MWCO Pore Size	NaCl % rej	$MgSO_4$ % rej	Cont ph Tol	Clean ph Tol	Temp Tol	Chlorine Tolerance
UF	PES	10,000 da	–	–	2~12	1~13	90°C	500 ppm
NF	TFC	240 da	61.70%	93.40%	2~11	1~11.5	60°C	<0.1 ppm

γ [s^{-1}], on the surface of the membrane during non-vibration mode can be calculated by the Eq. (8) [18]:

$$\gamma = \frac{4}{\frac{1}{2}h} \times v_{max} \quad (8)$$

where h is the height of the fluid [m], and v_{max} is the maximum velocity [m/s].

The volume reduction ratio, VRR [-], was defined as

$$VRR = \frac{V_F}{V_F - V_P} \quad (9)$$

where V_F is the volume of the feed [m^3] and V_P is the volume of the permeate [m^3] at any time.

The flux decreasing rate (FDR) [%] was expressed by the following equation:

$$FDR = \frac{J_{WA} \times 100}{J_{WB}} \quad (10)$$

where J_{WA} is the water flux of the fouled membrane after the separation experiment [m^3 m^{-2} s^{-1}] and J_{WB} is the water flux of the clean membrane before the separation experiment [m^3 m^{-2} s^{-1}].

2.6. Earlier results

The feasibility of the purification of dairy wastewaters, reported in our earlier study, was investigated by the same laboratory mode VSEP membrane device. Ultrafiltration (UF) membrane was tested using both vibration and non-vibration processes with the same parameters [19]. We found that the membrane module vibration significantly increased the permeate fluxes, even thought the rejection values did not increased significantly. In this earlier study mainly the effects of module vibration were investigated. In our present work both module vibration and the influences of the recirculation flow rate were investigated. Furthermore during this work both UF and NF membranes were tested. In the earlier study the milk powder concentration was 2.5 g dm^{-3}, while in this study it was 5 g dm^{-3} in the model wastewaters. This changed the ultrafiltration results compared to the previous study.

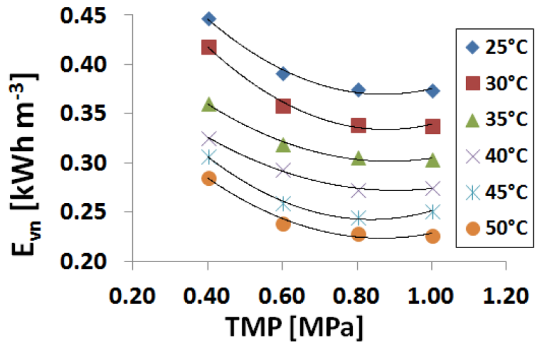

Fig. 2. The effect of water temperature on the non-vibration specific energy consumption (Ultrafiltration; A_v = 0; q_{vrec} = 16 dm^3 min^{-1}).

3. Results and discussion

3.1. Transmembrane pressure stepping experiments

The main goal of the TMP stepping experiments was to define the lowest energy consumption values. The non-vibration specific energy consumption (E_{vn}) per cubic metre of permeate was calculated from Eq. (5). The analysis of energy consumption variations with TMP were carried out with deionized water from 25 to 50°C during TMP stepping from 0.4 to 1.0 MPa and from 2.5 to 3.5 MPa in UF and NF respectively. As shown in Fig. 2, it was obvious that the energy consumption decreased with increasing temperature, which was caused by lower viscosity of water. It also shows that the lowest ultrafiltration energy consumption values were observed at 0.8 and 1.0 MPa. Since higher pressure can increase the operational cost, the lower TMP of 0.8 MPa was used in all further separation ultrafiltration experiments. In nanofiltration it was found that the energy consumption decreased with increasing TMP from 2.5 to 3.5 MPa for all tests. In this case a moderate TMP of 3 MPa was selected for the further experiments.

3.2. Separation experiments of model dairy wastewater

In the UF and NF separation experiments model dairy wastewater was filtered. The membrane fluxes with (V: vibration mode) and without module vibration (NV: non-vibration

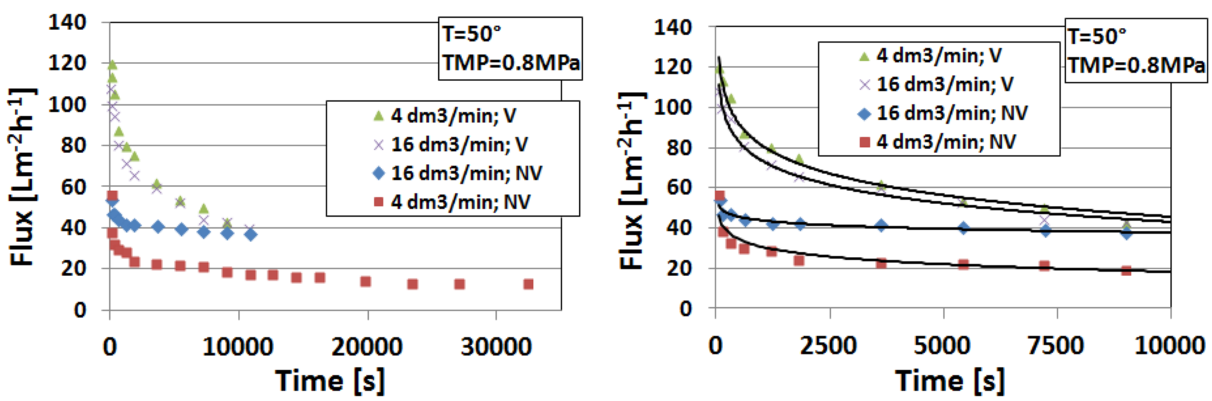

Fig. 3. The effects of recirculation flow rate and module vibration on ultrafiltration fluxes (V: vibration mode, A_v = 2.54 cm; NV: non-vibration mode).

Table 3
The calculated fluid velocity (v), Reynolds number (Re) and shear rate (γ) in the membrane module during filtration experiments

Non-Vibration mode					Vibration mode				
qv_{rec}		v	Re	γ	A [inch]	1	0.75	0.5	0.25
[dm^3 min^{-1}]	[m^3 s^{-1}]	[m s^{-1}]	[–]	[s^{-1}]	d [m]	0.0254	0.0191	0.0127	0.0064
					F [Hz]	54.1	53.6	53.9	52.6
4	0.004	0.228	8494	521	γ_{wmax} [s^{-1}]	129692	63949	96730	31084
16	0.016	0.913	33975	2085	γ_w [s^{-1}]	121908	60111	90925	29218

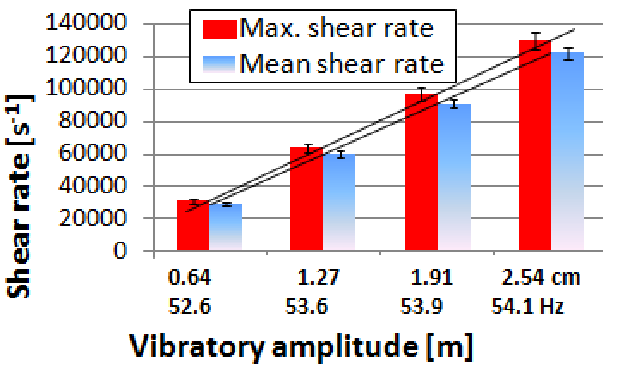

Fig. 4. The altering of mean and maximum shear rate as a function of vibratory amplitude.

mode) with low recirculation flow rate of 4 dm^3 min^{-1} and with high recirculation flow rate of 16 dm^3 min^{-1} were primarily studied. Experiments were carried out with both ultra- and nanofiltration, but only the ultrafiltration results were plotted in Fig. 3, because the tendencies were very similar. The highest average fluxes were observed in 4 and 16 dm^3 min^{-1} recirculation flow rate experiments with vibration. Unexpectedly, there was no significant difference between them.

It is interesting to note that, the flux increasing effect of recirculation flow rate was more pronounced during non-vibration mode due to 4 times higher shear rate on the surface of the membrane (Table 3). These results implied that the membrane fouling is greatly affected by shear rate.

The variation of mean and maximum shear rates was given by Eqs. (1), (2). As a result, the shear rate increases quasi linearly with vibratory amplitude as shown in Fig. 4.

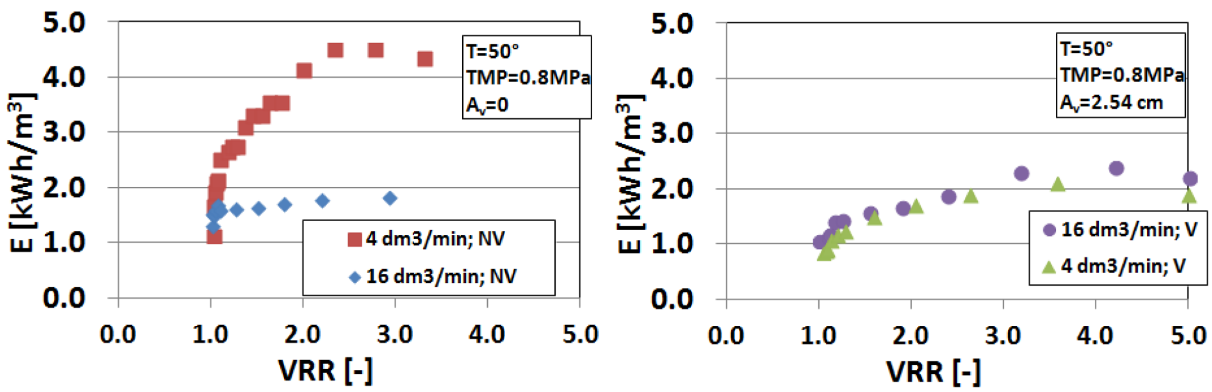

Fig. 5. Variation of specific energy consumption as a function of volume reduction ratio during ultrafiltrations (a, NV: non-vibration mode; b, V: vibration mode, A_v = 2.54 cm).

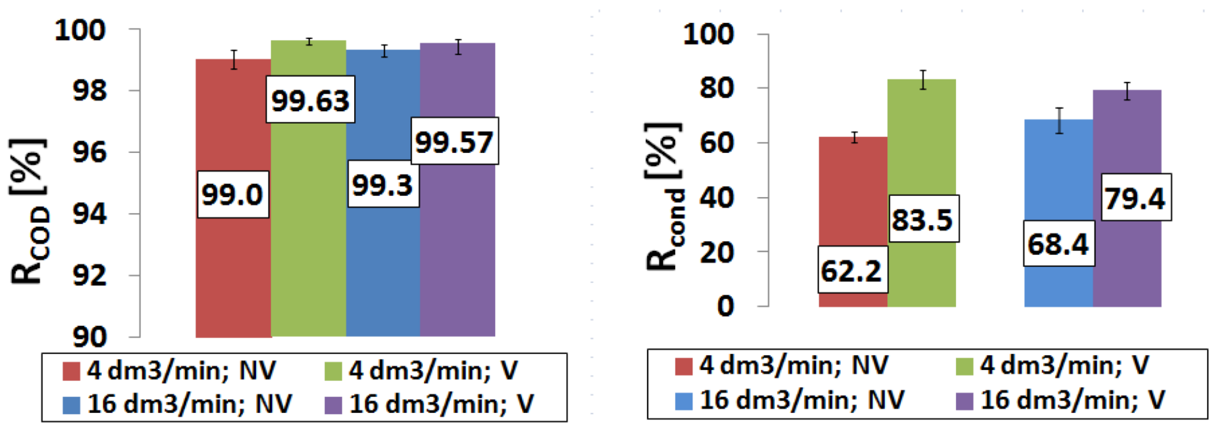

Fig. 6. Nanofiltration membrane rejections of chemical oxygen demand (a,) and total dissolved salt (b,) during the different experiments (NV: non-vibration mode; V: vibration mode, A_v = 2.54 cm).

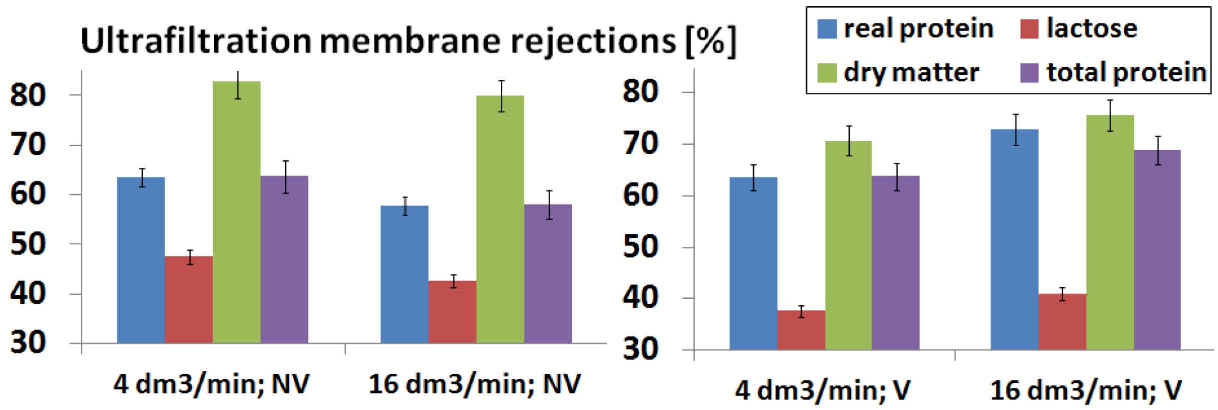

Fig. 7. Ultrafiltration membrane rejections of proteins, lactose and dry matter (a, NV: non-vibration mode; b, V: vibration mode, A_v = 2.54 cm).

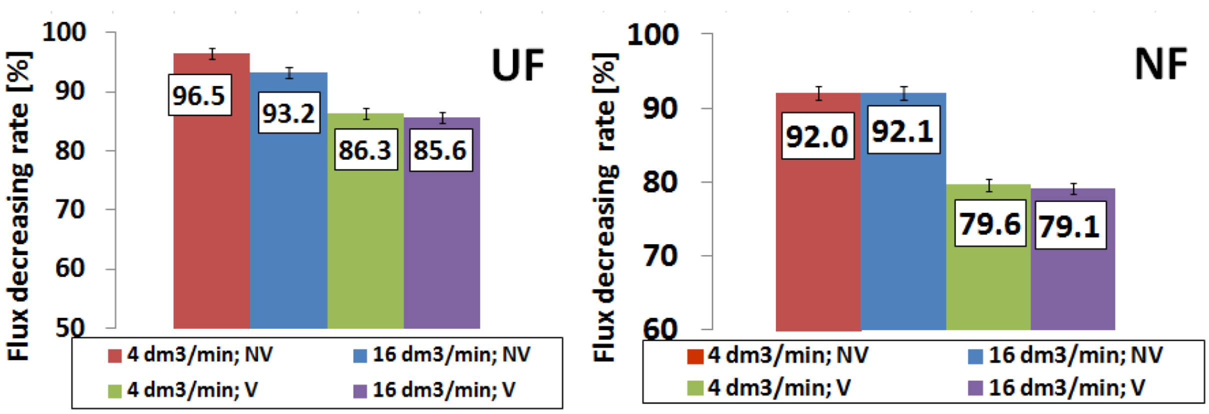

Fig. 8. Ultrafiltration and nanofiltration flux decreasing rates (NV: non-vibration mode; V: vibration mode, A_v = 2.54 cm).

By comparing the specific energy consumption of low and high recirculation flow rate experiments without vibration in Fig. 5a, it was found that the higher recirculation flow rate significantly decreased the energy consumption values, due to lower membrane fouling. The differences between them increased almost linearly with increasing VRR. As seen in Fig. 5b the energy consumption values of the low and high recirculation flow rate experiments with vibration were almost the same.

With regard to the quality of the nanofiltration permeate, Fig. 6 shows the NF membrane chemical oxygen demand (COD) and total dissolved salt rejections. Fig. 6a shows that the permeate COD quality depended non-significantly upon the recirculation flow rate and vibration. However the 240 Da NF membrane has high rejection properties for organic compounds and even salts (Table 2.). The recirculation flow rate increased the membrane salt rejections slightly in non-vibration mode. Vibration mode increased the salt rejection regardless of the flow rate.

In case of ultrafiltration membrane rejections of real and total protein, lactose and dry matter are shown in Fig. 7. In Fig. 7a it can be seen that the retentions slightly decreased using higher recirculation flow rate in non-vibration mode. However these differences were not significant. In Fig. 7b, it was found that the retentions increased using higher recirculation flow rate in vibration mode. Using higher flow rate, the polarized layer on the membrane might be more compact.

3.3. *Membrane fouling*

The water permeability loss or flux decreasing rates (FDR) of UF and NF membranes after separation experiments under different conditions: with low and high recirculation flow rate, with and without vibration; are shown in Fig. 8. The FDR for UF in non-vibration mode with low recirculation flow rate was higher than high recirculation flow rate, but there was no significant difference between them in vibration mode. The FDR for NF there were no significant differences between low and high recirculation flow rate experiments. However the FDR values were significantly lower in vibration mode than in non-vibration mode for both UF and NF.

4. Conclusions

In this study the feasibility of dairy model wastewater purification by ultrafiltration (UF) and nanofiltration (NF) membrane processes with membrane module vibration and non-vibration mode was investigated. From transmembrane pressure stepping experiments 0.8 MPa for UF and 3 MPa for NF were selected for the experiments. In the separation experiments, the highest average fluxes were observed at (low) 4 and (high) 16 $dm^3\ min^{-1}$ recirculation flow rate experiments with vibration, but there was no significant difference between them.

The shear rate caused by higher recirculation flow rate in non-vibration mode resulted in:

- significantly increased flux values,
- decreased specific energy consumption, and
- slightly increased membrane rejections in NF and decreased rejections in UF.

The shear rate caused by higher recirculation flow rate in vibration mode:

- resulted almost in the same fluxes, energy consumption and NF membrane rejection values, but
- slightly increased the membrane rejections in UF.

The higher shear rate caused by membrane module vibration:

- significantly increased the fluxes,
- decreased the specific energy consumption at low recirculation flow rate.

The water flux decreasing rate values, calculated as the ratio between the fouled and clean membrane fluxes, were significantly lower in vibration mode than in non-vibration mode for both UF and NF. However to understand the vibrated membrane module hydrodynamics on fouling mechanisms and the shear rates on the surface of the membrane in depth further investigation is needed.

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