

## EFFECT OF VIBRATION ON THE EFFICIENCY OF ULTRAFILTRATION

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### ABSTRACT

Nowadays, several environmental challenges are present to cope with. One with outstanding importance is the protection of our water supplies, therefore examination of wastewater treatment technology is a priority, especially in the European Union. In this work, the effect of membrane module vibration amplitude on the efficiency of ultrafiltration (*UF*) was investigated in a vibratory shear enhanced membrane filtration system. Based on the results of model dairy effluent *UF* and statistical analysis, the maximum vibration level available resulted in the most efficient filtration process, due to the most significant reduction of membrane fouling. From our results it was observed that the permeate fluxes more than doubled, specific energy demand was roughly halved, with almost identical retentions for organic matter, and total filtration resistance was reduced to less than half. Results also showed that setting the optimal operating parameters, an advantageous, efficiency focused, and sustainable wastewater treatment technology can be established.

Keywords: vibratory shear enhanced processing, ultrafiltration, dairy wastewater treatment, operational parameter analysis

### 1. INTRODUCTION

For the protection of our ecosystem, the protection of drinking and living waters has a special role. Food industry uses huge amount of water to meet high hygiene regulations and due to individual technological needs. According to United Nations Environment Programme (*UNEP*) [1], dairy industry is no exception, and its wastewater, if released into nature, poses a high environmental risk (e.g., eutrophication), due to its high organic content, but it is also a potential starting point for a circular economy by reusing valuable constituents. The use of membrane separation processes can be an excellent solution for the treatment of dairy wastewater [2, 3], as it reduces the load of organic matter, can be integrated into existing, continuous technology, and requires little or no addition of chemical compounds. The membrane itself is a semipermeable partition wall that separates components depending on their molecular weight cut-off (*MWCO*), material and the filtration circumstances. The *UF* method is based on mainly size exclusion, but reversible and irreversible reactions happen between the membrane surface and particles of the wastewater. In addition to its many advantages, the most significant disadvantage is membrane clogging/fouling, which greatly limits its long-term, large-scale applicability. There are basically three approaches to reduce blockage: optimizing the membrane material in order to minimize the attraction interactions, pretreating the wastewater to remove the most active clogging reagents and improving the design and operation of the membrane module, which reduces clogging through more efficient hydrodynamic flow [4]. Applied vibration is an example for improved module design and operation which was found beneficial by [5] and [6] in comparison with traditional procedures. Results from [7] shows that using a vibratory shear enhanced processing (*VSEP*) system decreased concentration polarization, the filtrate flux increased along with the transmembrane pressure and compared to conventional cross-flow filtrations, the energy consumption of *VSEP* was found to be significantly lower. As reported by [8], analysis with scanning electron microscope of the morphology of the membrane surface showed that without vibration, particles

were placed in a tight, dense manner while vibration was applied a more open, scattered particle distribution was observed. As stated by [9], despite having many advantageous properties, the *VSEP* technology is the sole property of an American company (New Logic Research, Inc.) and for this reason, research is relatively limited, but with the accumulation of appropriate theoretical and practical knowledge, a new, widely available technology could be developed. In our laboratory research, we aimed to investigate the effects of induced shear rate on the membrane surface, which can be resulted by membrane module vibration, while the main driving force of the process is the transmembrane pressure (*TMP*). The effect of vibration was investigated for efficiency parameters such as filtrate fluxes, membrane rejections for organic matter and milk constituents, values of specific energy consumption, and membrane filtration resistances. Our goal was to study and interpret the data obtained during laboratory work in order to find out which set of operating parameters, vibration amplitude and *TMP*, results in the most efficient filtration process due to the reduction of membrane fouling.

## 2. MATERIALS AND METHODS

### 2.1. Vibratory shear-enhanced processing (*VSEP*) membrane separation

Membrane separation tests were carried out on *VSEP* laboratory mode device (New Logic Research Inc., USA) with 30 kDa *MWCO* polyether sulfone membranes. Filtrations were performed in each case starting from 10 litres of freshly prepared and homogenized model wastewater made of concentration of 5 g dm<sup>-3</sup> skimmed milk powder and 0.5 g dm<sup>-3</sup> anionic detergent. The experiment setup, based on earlier studies, consisted of the combination of three vibration and the four *TMP* levels, resulting 12 separate experiments. Detailed parameters of the experiment series are in Tab. 1. Two-way analysis of variance was used to evaluate the measurements and calculated data of the mean values of each level with a confidence interval of 95% confidence level with Statistica 13.4 software (*TIBCO* Software Inc., USA).

Table 1. *VSEP* experiment setup with operating parameters

Parameter	Value											
$A_{vibr.}$ [m]	0.0000				0.0127				0.0254			
<i>TMP</i> [MPa]	0.6	0.8	1.0	1.2	0.6	0.8	1.0	1.2	0.6	0.8	1.0	1.2

### 2.2. Efficiency parameters

- a) Permeate fluxes: An important parameter in wastewater treatment is the amount of filtrate, which calculated for unit of time and membrane surface area is called flux, as in Equation (1). This characterizes the permeability of the membrane under certain conditions. A general goal is to produce as much filtrate as possible, but of course, total efficiency depends on energy investment and the permeate quality also.

$$J_{perm} = \frac{TMP}{\eta \cdot (R_M + R_{IRR} + R_{REV})} \quad (1)$$

, where  $J_{perm}$  is the permeate flux [m<sup>3</sup>m<sup>-2</sup>s<sup>-1</sup>], *TMP* is the transmembrane pressure [Pa],  $\eta$  is the dynamic viscosity of the solvent at 25 °C [Pas],  $R_M$  is the membrane intrinsic resistance [m<sup>-1</sup>],  $R_{IRR}$  is the irreversible resistance, which cannot be removed by rinsing, only by chemical treatment [m<sup>-1</sup>] and  $R_{REV}$  is the reversible clogging resistance [m<sup>-1</sup>], which is formed from the surface of the membrane due

to the removable polarization layer. Reversible and irreversible resistance values vary depending on flow conditions, pressure difference, temperature, and solution properties.

- b) Specific energy demand: it is economically and environmentally important to know how much energy is needed for production. In the case of membrane filtrations, this can be specified per unit of treated wastewater, the amount of filtrate. In our work, the specific energy consumption is used to generate 1 m<sup>3</sup> of filtrate calculated by Equation (2). Our goal is to achieve the lowest possible energy consumption. It is a question whether the flux increment is sufficient as a result of the vibration-reduced clogging or the use of extra energy by the vibromotor increases costs too much.

$$e = (P_{FP} \cdot \eta_1 + P_{VM} \cdot \eta_2) / (A \cdot J) \quad (2)$$

, where  $e$  is the specific energy consumption [kWh m<sup>-3</sup>],  $P_{FP}$  is the actual power of the feed pump [kW],  $\eta_1$  is the pump efficiency [%],  $P_{VM}$  is the actual power of the vibromotor [kW],  $\eta_2$  is the efficiency of the vibromotor [%],  $A$  is the membrane filtration surface [m<sup>2</sup>],  $J$  is the permeate flux [l m<sup>-2</sup> h<sup>-1</sup>].

- c) Membrane rejections: The tendencies of rejections, also known as retentions, which determine the quality of the filtrates, give an insight into the selectivity of the membrane under given condition. They show the percentage of a given component remaining in the concentrate relative to the starting solution by Equation (3). Our goal is to achieve the highest possible retention values, thus producing the clearest possible filtrate. Obviously, in line with what has been said so far, the filtration process must also be productive both in an economical and a sustainable way. In our experiments two types of rejections were calculated, one, rejections of organic matter based on chemical oxygen demand (COD), in order to control harmful environmental emissions, and two, the rejection of dairy particles in order to extract potentially recoverable parts that would otherwise go to waste. Rejections only for organic content will be later discussed.

$$R = \left(1 - \frac{c_P}{c_F}\right) \cdot 100 \quad (3)$$

, where  $R$  is the rejection [%],  $c_F$  is the concentration of the feed solution,  $c_P$  is the concentration of the permeate and the concentrations are always in the same dimension (e.g., [mg l<sup>-1</sup>]).

- d) Filtration resistances: In order to explore the sustainability of the filtration process and the possibility of long-term, industrial operation, we also calculated filtration resistances. Based on the resistance model, the flux of the permeate is, among other effects, inversely proportional to the value of the total resistance. The degree of total resistance depends on the type and degree of membrane clogging. There are three parts to total resistance indicated in Equation (4): the membrane's own resistance (which is constant under given conditions as in Equation (5)), reversible, and irreversible resistance. The reversible resistance is due to the concentration polarization layer formed on the surface of the membrane, it can be washed off and removed from the surface of the membrane calculated by Equation (6). Irreversible resistance is created by parts that clog the inner pores of the membrane, and its name characterizes the final, difficult-to-remove property of the clog, calculated by Equation (7). General goal is to minimize total resistance, and within that, to reduce the rate of irreversible resistance. Resistance values were calculated from data of water fluxes with the membranes before and after the ultrafiltration experiments with Equations (4-7).

$$R_T = R_M + R_{IRR} + R_{REV} \quad (4)$$

$$R_M = \frac{TMP}{J_{before} \cdot \eta_W} \quad (5)$$

$$R_{IRR} = \frac{TMP}{J_{after} \cdot \eta_W} - R_M \quad (6)$$

$$R_{REV} = \frac{TMP}{J_{constant} \cdot \eta_{WW}} - R_M - R_{IRR} \quad (7)$$

, where  $R_T$  is the total,  $R_M$  is the membrane,  $R_{IRR}$  is the irreversible and  $R_{REV}$  is the reversible resistance [ $m^{-1}$ ].  $J_{before}$  is the measured water flux before,  $J_{after}$  is the measured water flux after filtration and  $J_{constant}$  is the stabilized permeate flux during filtration [ $m^3 m^{-2} s^{-1}$ ],  $\eta_W$  is the dynamic viscosity of water,  $\eta_{WW}$  is the dynamic viscosity of model dairy wastewater at 25 °C [Pas].

### 3. RESULTS AND DISCUSSION

#### 3.1. Permeate fluxes

On Fig.1 flux values are shown. On average, without vibration fluxes were  $22.4 \text{ lm}^{-2}\text{h}^{-1}$ , with intermediate vibration  $40.7 \text{ lm}^{-2}\text{h}^{-1}$ , and with maximum vibration  $47.8 \text{ lm}^{-2}\text{h}^{-1}$ . It is visible that the maximum vibration resulted in the highest mean flux value, which is more than two times than without vibration. Based on two-way analysis of variance, the effect of different vibration levels resulted in significant differences between the filtrate flux values ( $p < 0.05$ ), the significant difference is between 0 m and 0.0127 m, and 0 m and 0.0254 m amplitude levels. We can deduce the effect of vibration on reducing membrane clogging. According to [10], during this process, the filtered liquid remains almost stationary compared to the intensely vibrating membrane, so the surface shear force is greatly increased, as a result of which the clogging particles are removed, the concentration polarization decreases and the amount of permeate increases.

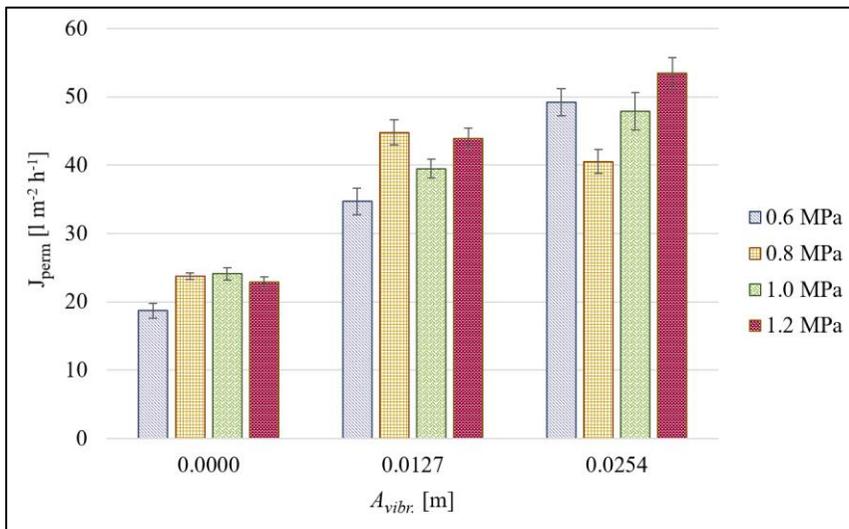


Figure 1. Permeate flux change as function of vibration amplitude (MWCO: 30 kDa;  $q_{rec}=0,9085 \text{ m}^3 \text{ h}^{-1}$ ;  $T=25 \pm 1 \text{ }^\circ\text{C}$ )

### 3.2. Specific energy demand

Shown on Fig. 2. specific energy consumption values were on average  $0.70 \text{ kWhm}^{-3}$  without vibration,  $0.43 \text{ kWhm}^{-3}$  with intermediate vibration,  $0.38 \text{ kWhm}^{-3}$  with maximum vibration. It is visible that the maximum vibration level resulted in the lowest energy consumption, which is almost half of the average value measured without vibration. Based on the two-way analysis of variance, the effect of different vibration levels resulted in a significant difference between the specific energy consumption values ( $p < 0.05$ ), the significant difference is between 0 m and 0.0127 m, and 0 m and 0.0254 m amplitude levels. Interestingly, as specific energy demand is calculated per filtration volume, the additional amount of energy used by the intensified vibration could improve efficiency as it derived multiple increase in permeate flux in proportion to the energy used by the vibromotor.

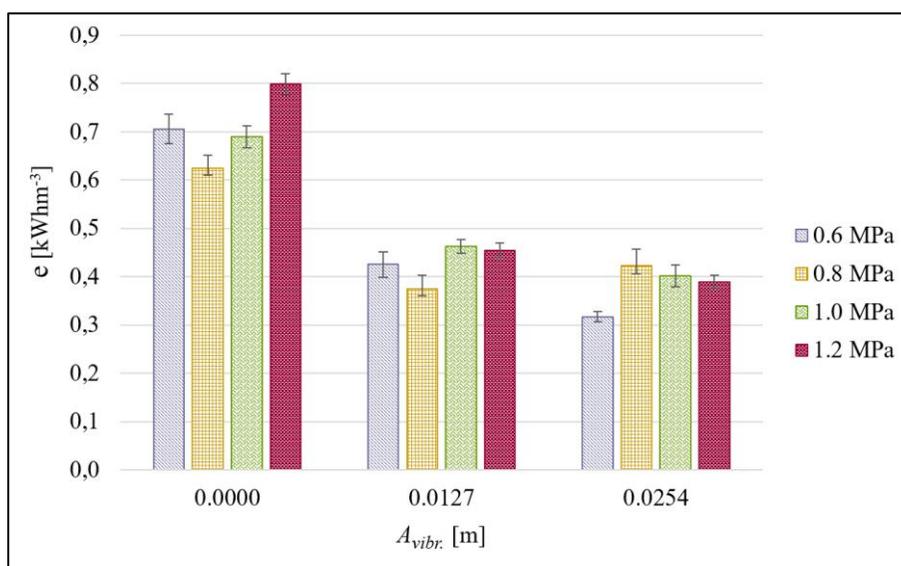


Figure 2. Specific energy demand change as function of vibration amplitude (MWC0: 30 kDa;  $q_{Vrec}=0,9085 \text{ m}^3\text{h}^{-1}$ ;  $T=25\pm 1 \text{ }^\circ\text{C}$ )

### 3.3. Membrane rejections

Controlling adverse environmental effects is a priority in wastewater treatment, for organic matter emission rejections are calculated by chemical oxygen demand. Our results are shown on Fig. 3. The average rejection values for organic matter per vibration level were 70.8% without vibration, 73.1% with intermediate vibration, and 71.3% with maximum vibration. Based on the two-factor analysis of variance, the effect of different vibration levels did not result in a significant difference between the retention values for organic matter ( $p > 0.05$ ). Due to differences in filtration types and other mechanisms yet to be explored, our results are very similar, apparently independent from the effects of vibration.

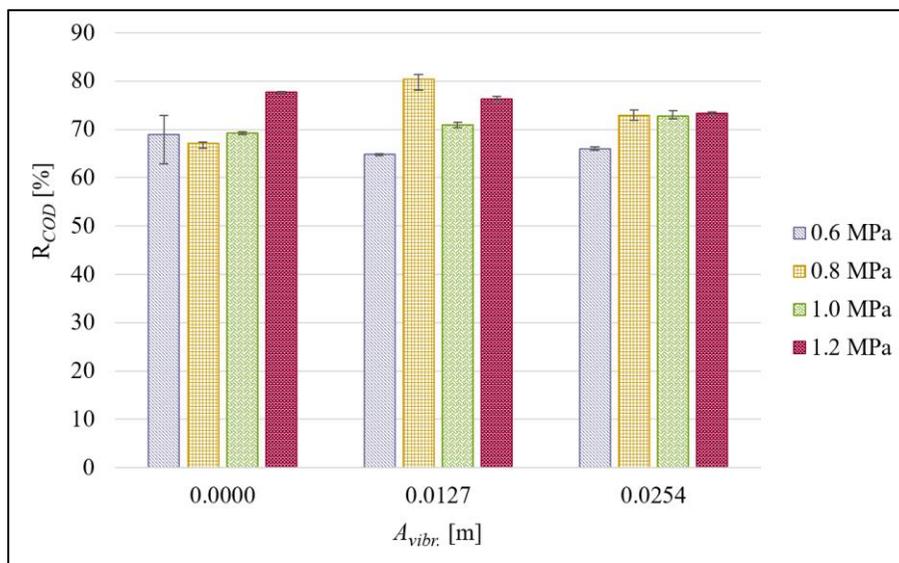


Figure 3. Membrane rejection for chemical oxygen demand change as function of vibration amplitude (MWC0: 30 kDa;  $qV_{rec}=0,9085 \text{ m}^3\text{h}^{-1}$ ;  $T=25\pm 1 \text{ }^\circ\text{C}$ )

### 3.4. Filtration resistances

On Fig. 4, the total filtration resistance values are illustrated according to the three vibration amplitude levels to provide a more insightful analysis of the effect of vibration. Total resistance consists of three parts. First, the membrane's own resistance, which is constant under given conditions. Second, the reversible resistance caused by concentration polarization formed on the membrane surface, which can be washed off and removed. Third, the irreversible resistance, which is created by parts that clog the inner pores of the membrane, and its name characterizes the final, difficult-to-remove property of the clog. The average total resistance values on vibration levels were  $170 \cdot 10^{13} \text{ m}^{-1}$  without vibration,  $102.4 \cdot 10^{13} \text{ m}^{-1}$  with intermediate vibration, and  $76.4 \cdot 10^{13} \text{ m}^{-1}$  with maximum vibration. The maximum vibration level resulted in the lowest total resistance, which is less than half without vibration. Within this, the ratio of reversible to irreversible resistance is important.

We observed a trend that with increasing vibration, the value of reversible, easily removable resistance decreased greatly, while the values of irreversible resistance decreased slightly in the same way. The trend is certainly due to the vibration-induced membrane clogging reduction and the change in membrane surface flow conditions. Based on the two-factor analysis of variance, the effect of different vibration levels resulted in a significant difference between the values of reversible and irreversible resistance in addition to the total filter resistance ( $p < 0.05$ ). For all three resistance values, the significant difference is between 0 m and 0.0127 m, and 0 m and 0.0254 m amplitude levels.

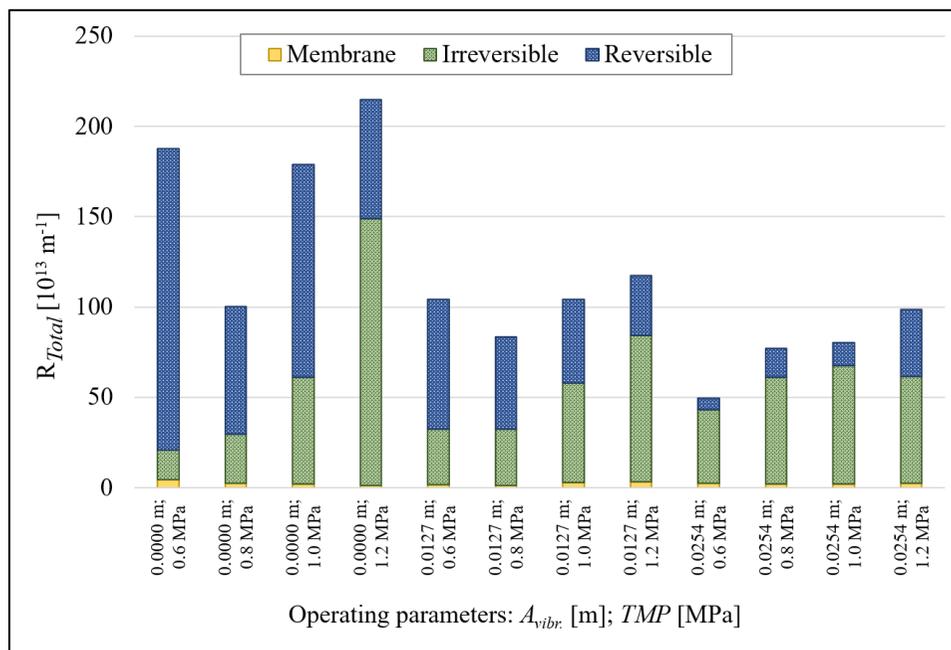


Figure 4. Membrane resistance change as function of operating parameters (MWC0: 30 kDa;  $qV_{rec}=0,9085 \text{ m}^3\text{h}^{-1}$ ;  $T=25\pm 1^\circ \text{C}$ )

## 4. CONCLUSIONS

The effect of the vibration amplitude for filtration efficiency was investigated by VSEP ultrafiltration with model dairy wastewater. 12 separate experiments were executed, and results were analysed statistically to establish trends to characterize best available operating parameters that ensure adequate performance. Four efficiency parameters were studied. First, the permeate flux, which also characterizes the amount of treated wastewater and the time course of filtration. The second indicator is of economic and environmental significance, this is the specific energy consumption, which can be used to compare different treatments per unit of treated wastewater. The third indicator is the membrane rejection, which characterizes membrane selectivity, also for organic materials to control harmful environmental emissions, as well as for milk producers, due to the recovery of potentially recoverable valuable components. Lastly, the type and severity of total, reversible, and irreversible filtration resistances, which can provide a picture for a long-term, industrial operation. Based on our results, the maximum vibration level resulted in the most efficient filtration process for all four parameters. As a result of reduced membrane clogging due to vibration, permeate fluxes more than doubled compared to the least efficient process, specific energy consumption was roughly halved, with almost the same, standard rejection values, and total filtration resistance was reduced to less than half. The beneficial effect of applied vibration in ultrafiltration is remarkable and further investigation of other operating parameters can help establish an economical wastewater treatment technology that will also serve sustainable development and the protection of our environment in the long run.

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