Investigation of Membrane Fouling in Vacuum Membrane Distillation (VMD) Using Blocking Filtration Laws [†]

Wajeeha Bibi ^{*}, Muhammad Asif and Jawad Rabbi

Faculty of Mechanical Engineering, GIK Institute of Engineering Sciences and Technology, Topi 23460, Pakistan; masif@giki.edu.pk (M.A.); jawad.rabbi26@gmail.com (J.R.)

^{*} Correspondence: wajeehamalikzaman@gmail.com

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Abstract: VMD is one of the desalination technologies used for drinking water purification because of its higher permeate flux and lower energy consumption, and it uses low grade energy for operation. However, there are some critical problems related to VMD, one of which is membrane fouling. In the present study, the fouling phenomenon in VMD is investigated using constant pressure-blocking filtration laws. The results of constant pressure-blocking filtration law indicated that the permeate flux was initially unaffected by the cake layer, but with the passage of time as the pores began to constrict, a formation of a relatively thick cake layer was observed, which resulted in the decrease of permeate flux.

Keywords: blocking filtration laws; membrane fouling; membrane distillation; VMD

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1. Introduction

VMD is one of the most effective desalination technologies. During the VMD process, membrane scaling and fouling happens, and a cake layer forms on the membrane–feed interface that causes a reduction in flux. The resistance to flow due to cake formation becomes dominant with the duration of the desalination process [1]. Yun et al. [2] studied membrane fouling for high-salinity NaCl solutions in direct contact membrane distillation and reported that permeate flux decreases as the concentration of salt increases. Bhausaheb et al. [3] researched on ground water and salt solution desalination using a vacuum membrane distillation unit and showed a 29% decrease in permeate flux over a time period of 75 h for ground water.

2. Modeling Procedure

The general form of constant pressure blocking filtration laws is represented as:

$$\frac{d^2t}{dV^2} = k \left(\frac{dt}{dV} \right)^n \quad (1)$$

where $t(\text{sec})$ is the filtration time, $V(\text{m}^3)$ is the cumulative volume, k is a coefficient of fouling and n is the parameter depending on fouling trait. The blocking laws shown in Figure 1, presented by Hermia [4], described the fouling process by four models: (i) standard model of pore blocking; (ii) intermediate model of pore blocking; (iii) complete pore blocking model; and (iv) cake filtration model of blocking. The four models are presented in Table 1.

Figure 1. Membrane blocking by fouling. (a) Pore blocking (b) Intermediate blocking (c) Standard blocking (d) Cake layer.

Table 1. Blocking filtration models.

	Linearized Form	n	Assumption
Standard Blocking	$\frac{t}{V} = at + b$	1.5	Deposition of particles smaller than the pore size resulting in smaller pores
Intermediate Blocking	$\frac{1}{J_V} = at + b$	1	Particles super-impose on each other.
Complete Blocking	$-\ln\left(\frac{J_V}{J_{V,0}}\right) = at + b$	2	Membrane pores are completely sealed off by the particles
Cake filtration	$\frac{t}{V} = aV + b$	0	Particles deposit on membrane-feed interface forming a cake layer

We used an approach similar to Yun [2] and applied the cake filtration model on the last region of the experiment which could be observed as linear. The cake filtration law parameters “a” and “b” are presented in Equations (2) and (3), respectively. These equations were applied to the results obtained from linearized cake filtration model to evaluate the specific cake resistance and clean membrane resistance.

$$a = \frac{\mu \cdot \alpha_c \cdot S}{2 \cdot A^2 \cdot TMP} \quad (2)$$

$$b = \frac{\mu \cdot R_m}{TMP \cdot A} \quad (3)$$

where μ is the viscosity of water in $\text{Pa} \cdot \text{s}$ calculated from seawater correlations provided by Alsaadi [5], α_c is the specific cake resistance, S is salinity of feed water, A is area in m^2 , TMP is the trans-membrane pressure in kPa , and R_m is the clean membrane resistance in m^{-1} .

3. Results and Discussion

3.1. Experiment 1

The experimental data were linearized. Figure 2a represents the standard blocking model applied on Experiment 1. The solid line represents the linear fit of the model, and the dashed lines are the prediction intervals of the linear fit. The residual sum of the squares value, which was calculated as 0.99, represents a good fit for the points. The result shows that for the initial time up to 23 h, standard blocking law fits the filtration data, resulting in a clear representation of membrane pore constriction. Figure 2b represents the cake

filtration model. The model fits with a residual sum of squares value (R-sq) of 0.9999, as the last three points were observed to be linear.

Figure 2. Application of blocking filtration laws on Experiment 1: (a) standard model, (b) cake filtration.

3.2. Experiment 2

Figure 3a represents the linear fit of standard model on the first part of Experiment 2. The initial three points were seen in a linear region; thus, the model was applied to this region. For Experiment 2, pore constriction is predicted linearly and continuously until 9.5 h. This value is less than the value for Experiment 1, which is explained by the different input conditions and specifically the membrane pore size. Therefore, pore constriction would have a higher impact and cause a greater amount of fouling in a lesser duration. The cake filtration model is presented in Figure 3b. The model was applied on the last five points of the data as they were observed as linear and when the R-squared value was evaluated, it achieved 0.988 corresponding to a good fit for the data points.

Figure 3. Application of blocking filtration laws on Experiment 2: (a) standard model, (b) cake filtration.

3.3. Experiment 3

Experimental data from Bhausaheb [3] were utilized as Experiments 3 and 4. The results of Experiment 3 when linearized by t/V vs. t were observed to have a zero gradient and moved horizontally until 70 h. Due to this, the standard blocking model is inapplicable as we assume the pore blocking to be dominant during the initial time of the experiment. Figure 4a represents the cake filtration model that was applied to the last four points due to their linearity, and R-square was calculated to be 0.991, presenting a good fit for the data points to the linearized cake model.

Figure 4. (a) Application of blocking filtration laws on Experiment 3: cake filtration; (b) application of blocking filtration laws on Experiment 4: cake filtration.

3.4. Experiment 4

Similarly, for Experiment 4, the standard blocking model could not be applied because the plot of t/V vs. t was horizontal and no slope existed. The cake model was applied on the last five points of the experiment and achieved an R-squared value of 0.822, which is the lowest from all the four experiments, as illustrated in Figure 4b. αc was calculated from Equation 12 as 12.4×10^9 kg/m, which is the highest calculated of the four experiments. The intercept was negative for this experiment. Therefore, the clean membrane resistance could not be calculated.

4. Conclusions

The use of blocking filtration laws helped in predicting the fouling. Predicting fouling is a difficult task as these processes are usually simultaneous with their effects varying with time, such that when the filtration begins, a cake layer starts to form. This would vary based on the operating conditions, and simultaneously some feed particles could also block the pores or constrict them. Thus, at the start of the filtration process, the pore blocking phenomenon would be dominant along with pore constriction, but as time proceeds, a cake layer forms, which could contribute a dominating role in the reduction in flux, and the effects of pore constriction would become lesser as compared to the cake layer.

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