Modeling Filtrate Processes in Pre-treatment Experiments for Reverse Osmosis Desalination Plants

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Introduction

Demand for freshwater supplies is exceeding production capabilities in many areas around the world. To fill this demand many states are turning to desalination, specifically the construction of desalination plants using reverse osmosis (RO) to produce potable water from sea, brackish or riverine sources. Conceptually, RO is a simple membrane separation process, where water from a solution is separated from dissolved materials as it is forced under pressure through a membrane. The need to monitor the feedwater going to the RO unit to determine its membrane surface fouling potential is particularly important. Monitoring this fouling tendency is a challenge, because feedwater fouling tendencies usually go noticed until the membranes are damaged. This results in expensive downtime or in worse case scenarios, membrane replacement.

The American Society for Testing and Materials (ASTM) [1] has published procedures for a simple test to determine the silt density index (SDI) of RO feedwaters. The ASTM test involves placing a 47 mm filter disk (with 0.45 micron pore size) in a filter holder. The feedwater is passed through the filter at 30 psi. The amount of time required (t_i) for the 500 ml of feedwater to pass through the filter is recorded. As the feedwater continues to pass through the filter repeat the 1st step at 5, 10 and 15 minutes. The SDI is calculated using the following equation:

$$SDI_T=100[1-(t_i/t_f)]/T \qquad (1)$$

T is normally 15. SDI_{15} <4 or <5 is considered suitable for RO feed by RO makers. [1]

Although the SDI test is currently recognized as one of the best ways to predict the fouling potential of feedwater, some researchers point out that SDI_{15} is not accurate enough to predict water fouling ability [2, 3, 4]. For instance, in an experiment using water added fouling matter, no clear correlation between the performance of RO and the level of SDI_{15} was found. As an alternative, the modified fouling index (MFI) was proposed from physicochemical point of view [5].

The objective of this study is to develop a statistical model of the filtrate process for the ASTM filtering experiment performed in desalination plants. We sampled seawater with various fouling conditions and conducted filtering experiments. Statistically analyzing the data, we established a statistical model for the filtrate process to understand the problems of SDI_{15} and to develop a better fouling potential index.

Background

The total amount of water filtered, say V, over a sufficient duration is considered the best parameter for developing a water quality index. Nevertheless, V is not used as a fouling index, since it depends on measuring devices as well as water quality. That is, a fouling index should not be influenced by the measuring devices [6], since most RO membrane manufacturers specify the operating range of SDI_{15} such as $SDI_{15}<4$ or <5 for water supplied to the RO membrane irrespective of measuring devices. Thus, we hypothesized that if SDI_{15} reflects precisely the permeability change due to the fouling from the beginning to the end of the experiment and if the experiment uses the same measuring device, then SDI_{15} and V should be closely related with each other irrespective of the measuring device. In a previously conducted experiment [7] to examine the effects of filter holders on V_{15}, or the amount of water filtered in 15-minutes, SDI_{15}, and MFI, three different holders (0:Advantec KS-47; 1:Millipore XX4304700; 2:Millipore XX4404700) and three different water samples (1: raw water; 2: MF (micro filtration) water; 3 : MF water stored 1 day) and a Millipore 0.45μm pore size by 47mm ϕ filter were used. The results are tabulated in Table 1.

Table 1: ANOVA results on the effects of holders and water on filtration

No	Water	Holder	V_{15}	SDI_{15}	MFI	logMFI
1	1	0	4093	6.46	46.68	3.84
2	1	1	4547	6.48	36.23	3.59
3	1	2	3380	6.42	69.08	4.24
4	2	0	9593	4.65	5.21	1.65
5	2	1	10585	4.47	3.99	1.38
6	2	2	8537	4.41	6.05	1.80
7	3	0	11011	3.96	3.15	1.15
8	3	1	12385	3.92	2.50	0.92
9	3	2	10044	3.96	3.85	1.35

	Water	Holder
V_{15}	<0.001	0.006
SDI_{15}	<0.001	0.342
logMFI	<0.001	0.003

P-value by ANOVA

ANOVA was performed to find the significance of water and holder on each of the items. Water was significant for all items. On the other hand, holder had significant effects on V_{15} and logMFI but not on SDI_{15}, indicating that only SDI_{15} can be appropriate for a fouling index. As expected, V_{15} and SDI_{15} are closely related with each other when the same holder was used.

Methods

Ideally, no deterioration occurs with unfouled water, therefore V_t should be proportional to the time elapsed, that is V=μT, if pure water is used in the filtrate experiment, where μ is determined by the experimental and environmental conditions. Taking logarithm, we have logV=logμ+logT. This indicates that when the water contains no foulant, logV and logT should have a linear relationship with slope 1. The relationships between the amount of filtrated water (V) and elapsed time (T), will be analyzed based on the linear regression model

$$\log V = \alpha + \beta \log T + \varepsilon\,,\ \ \varepsilon \sim \mathrm{N}(0,\sigma^2) \qquad (2)$$

Let us assume that the effect of an environmental factor X is multiplicative through a study period with a constant c(X) such that the relationship $V=e^{\alpha}T^{\beta}e^{\varepsilon}$ is modified to $V=c(X)e^{\alpha}T^{\beta}e^{\varepsilon}$, or $V=e^{\alpha+\log c(X)}T^{\beta}e^{\varepsilon}$. Putting $\alpha^* = \alpha + \log c(X)$ lead to the same model as (2). That is, such factors affect α but not β in (2). Differentiating (2) by β, we have $dV/dT = \beta(V/T)$, indicating that an instantaneous permeate rate at T is proportional to the average permeate rate up to T with the proportional constant β. We will examine the performance of β as a fouling index.

It is straight forward to show that SDI_{15} and β are related as

$$\frac{t_f}{t_i} = \left\{1+\left(\frac{15}{t_i}\right)^{\beta}\right\}^{1/\beta} - \left(\frac{15}{t_i}\right) \qquad (3)$$

if the model (3) holds throughout the experiment.

We conducted filtrate experiments to examine the performance of SDI_{15} as well as the validity of the above model under a variety of conditions. We used one of the same measuring devices, the Advantec KS-47 and the same Millipore filter, as in our previous experiment to make V_{15} the standard in evaluating the performance of SDI_{15} and β. Out of 187 samples taken, 72 were raw water, 30 dual media filtration seawater, 52 MF seawater, and 33 coarsely filtered seawater. Temperature (℃), electric conductivity (EC), pH, E260, turbidity, and volume of water treated were measured every 5 seconds. SDI_{15} was obtained for each sample after the experiment. Capacity of the experimental apparatus allowed for maximum 12,000ml of water to be measured.

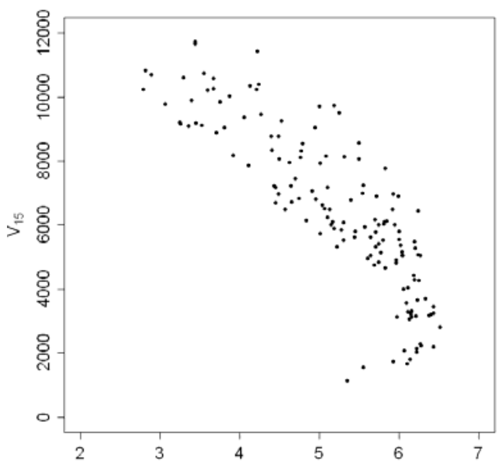

Figure 1. Scatter plot of SDI_{15} and V_{15}

Results

Figure 1 shows the filtrate processes of all samples in which the apparatus capacity prevented V_{15} recording of 32 samples with low turbidity. Figure 2 shows the scatter plot for V_{15} and SDI_{15}. The nonlinear relationship observed in high turbidity waters with $V_{15}<2200$ was repeatedly pointed out as a defect with SDI_{15} [8].

Figure 3 shows the relationship between t_i and t_f. This indicates that t_f depends heavily on the quality of water but t_i is approximately 30 seconds for most of the water independent of t_f with the exception of some water with large t_f >500. Water with t_f >500 and t_i>50 comprise the nonlinear part of Figure 2. This finding is in accordance with [9]. The results suggest that SDI_{15} is mostly determined by the value of t_f if SDI_{15} is measured using the same device under similar environments, which is usually the case in desalination plants.

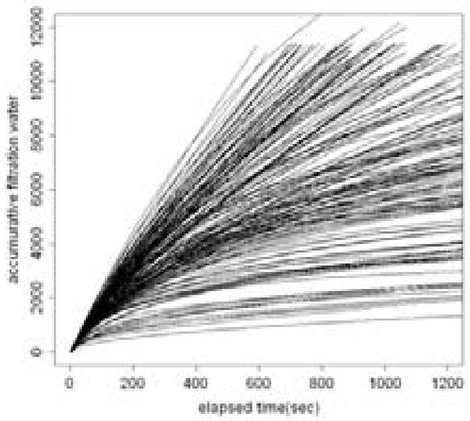

Figure 2. The filtrate processes of the samples.

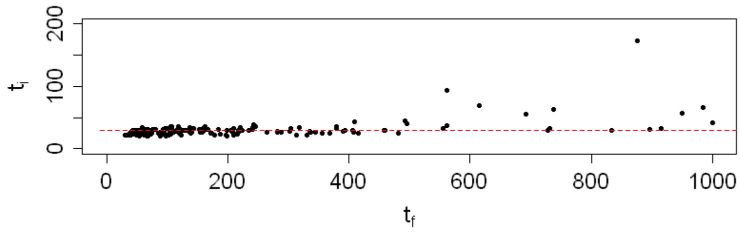

Figure 3. The relationship between t_i and t_f.

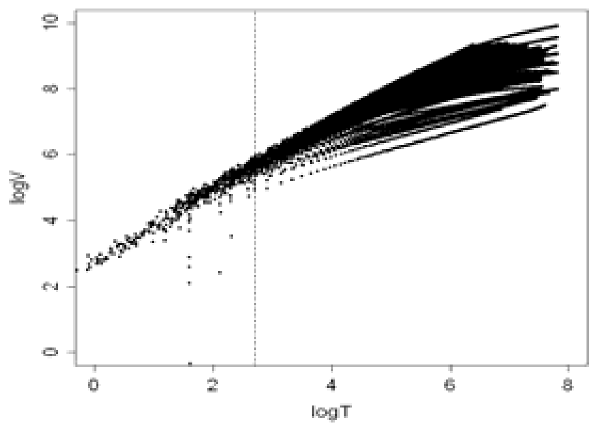

Figure 4. The processes in log-log scale.

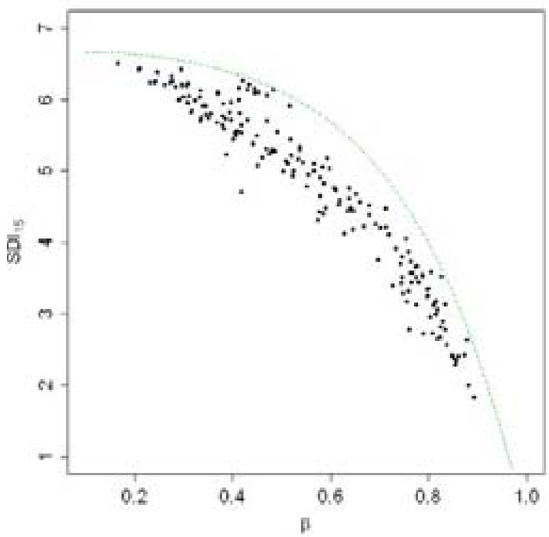

Figure 5. Relationship between β_T and SDI_{15}

Figure 4 shows the processes in log-log scale. Since the processes generally appear nonlinear, we extend the model (2) to a piecewise linear model with five change points such that t_1^* =log60, $t_2^* = \log 270$, $t_3^* = \log 480$, $t_4^* = \log 690$ and $t_5^* = \log 800$, and with $T^* = \log T$

$$\log V = \alpha + \beta_0 T^* + \sum_{k=1}^{3} \beta_k \langle T^* - t_k^* \rangle + \beta_T \langle T^* - t_5^* \rangle + \varepsilon \qquad (4)$$

where <x-c>=Max(0, x-c) equals 0 for $x \le c$ and x-c for x>c, a piecewise linear function with one change point at x=c, and ε is a random variable following $N(0, \sigma^2)$. The slope of the last line is denoted by β_T. Those change points were arbitrarily chosen except for t_5^*. Our first choice was $t_5^* = \log 900$ (15min), but the interval beyond log900 was too short to determine a reliable value of β_T.

Figure 5 shows that SDI_{15} and β_T are closely related. This is because, for most water samples, SDI_{15} is determined by the process V(T) in T>900 since t_i is approximately 30. Testing with the data of Table 1 showed that the effect of holder on β_T was not significant (p=0.42). Thus, β_T can be considered as a fouling index, but it showed similar nonlinearity with V_{15} as shown in Figure 1. That is, it has the same defect as SDI_{15}. The graph of SDI_{15} calculated from (3) with t_i=30 and $\beta=\beta_T$ is also shown in Figure 5. Their outlines` are similar but the observed SDI_{15} is consistently lower than the calculated one. To explain this reason, the filtrate process of a sample and the piecewise linear line (4) fitted to the sample were displayed in Figure 6(a). Since the two lines overlap, the former is shown by sparsely chosen dots and the latter a solid line with the five change points. β_T =0.34 for this particular sample. The graph of the line (3) with β=0.34 which passes (log30, log500) is also shown. Figure 6(b) shows the filtrate process of the sample and the line in the original scale. The SDI_{15} of the sample was 5.74. Whilst, the SDI_{15} calculated from (4) with β=0.34 and t_i=30 is 6.49. This discord arises from the fact that β_T is obtained from a too late stage where the model (2) does not.

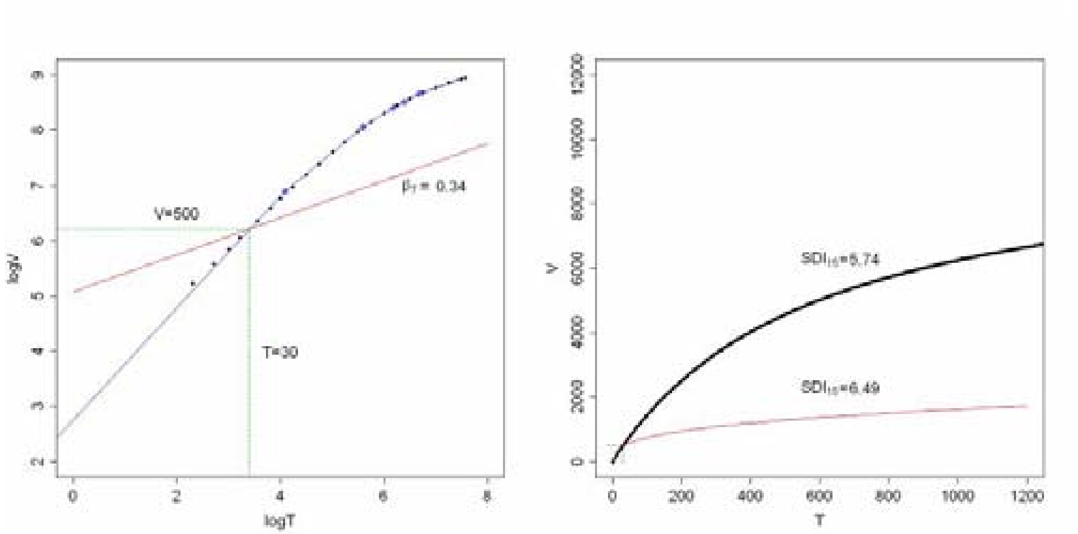

Figure 6. The filtrate process of a sample and the piecewise linear line fitted to it (left) and the graph of the model (3) with $\beta=\beta_T$ which passes (log30, log500) (right).

In fact, our preliminary report [7] found that β obtained from applying model (2) to an earlier interval (log60, log540) showed approximately linear relationships with V_{15}. These results suggest that the nonlinearity between SDI_{15} and V_{15} (Figure 1) may be due to the fact that SDI_{15} uses t_f obtained from a too late stage where model (2) no longer fits. In conclusion, model (2) is a key to understanding the nature of the filtrate process and β will be a better fouling index than SDI_{15}. However, a systematic approach to determine the best interval for β in more general setting and the physicochemical aspects of it are left for future work.

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Abstract

RO is becoming a most popular instrument to desalinate seawater as a result of new developments in membrane technology. The critical factor for the cost-effective long-term performance of RO in desalination plants is fouling caused by turbidity of seawater. To reduce the turbidity, the seawater is first treated by sand, film, or others, to obtain the so-called "pre-treated seawater". To assess the fouling potential of the pre-treated seawater should be quickly and accurately performed.

Silt density index (SDI) is a standard measure of the fouling potential of the pre-treated seawater on a membrane surface. SDI_{15} is widely used as a fouling index of the pre-treated seawater. However, some literature indicate that SDI does not always correctly represent the fouling potential and alternative measures, such as the modified fouling index, were proposed from physical and biochemical view points. Nevertheless, the statistical nature of those indices has not been well documented. This study shows the usefulness of statistical modeling of the filtrate process in the desalination plant operation where deep statistical analyses were rarely conducted.