Searching for an Efficient Fouling Index for Reverse Osmosis Desalination: A Statistical Approach

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Abstract

Desalination using a reverse osmosis (RO) membrane is a complex process that requires preventive maintenance to control the fouling potential of feed water for long-term successful operation. Fouling is caused by scaling, bacterial growth, or the deposition of suspended or dissolved substances. The widely accepted measure of the fouling potential is the silt density index (SDI). We conducted filtering experiments under diverse conditions to gain new insight into the performance and deficiencies of the SDI from a statistical point of view. Based on the results, we developed a new fouling index that is more reliable and feasible than the SDI.

Keywords
SDI, permeation coefficient, fouling, desalination, statistical analysis

1. Introduction

The reverse osmosis (RO) membrane is becoming a popular instrument to desalinate seawater as a result of new developments in membrane technology. Since RO desalination is a highly complex physicochemical process, an efficient and accurate control system is required to maintain optimum operating conditions. Corrective action and preventive maintenance based on key factor measurements form an essential part of the process control for long-term successful operation of RO desalination plants. Most of these measurements, such as pH, temperature, flow rate, turbidity, *etc.*, are obtained on-line at equal intervals and logged in a database. The detailed analysis to estimate the fouling potential of the water is performed off-line in central laboratories following standard methods. Fouling is caused by scaling, bacterial growth, or the deposition of suspended or dissolved substances. Accurate estimates of the fouling potential of feed water are the most important factor for ensuring the successful operation of an RO membrane [1]. The most common and widely accepted measure is the silt density index (SDI), which is determined based on the filtration of feed water through a 0.45-μm membrane under a constant pressure [2]. Because the quality of the water is affected by external disturbances, such as pH, temperature, pressure, and flow rate, the SDI is measured several times a day to detect any trends in fouling and ensure that optimum preventive measures or corrective actions are taken. RO desalination plants operate with a number of units, and the SDI is monitored for each unit. We conducted filtering experiments under diverse conditions and statistically analyzed the relationships between the amount of filtered water, elapsed time, and environmental factors. The objective of the experiment was to gain new insight into the performance and deficiencies of using the SDI from a statistical point of view. Based on our results, we developed a new fouling index that is more feasible as well as more reliable than the SDI.

2. Filtration Experiment for the SDI

SDI is defined by

$$SDI_T = \frac{\left(1 - {t_i}/{t_f}\right) \times 100}{T} \quad (1)$$

where T is the total elapsed test time, normally 15 minutes, t_i is the time required to collect the initial 500 ml of filtrate, and t_f is the time required to collect the final 500 ml of filtrate [3]. Some RO membrane manufacturers specify an SDI_{15} operating range, such as $SDI_{15} < 4$ or $SDI_{15} < 5$, for water to be supplied to the RO membrane. It is widely accepted that the SDI_{15} value depends little on the environmental or experimental conditions, and a number of studies in the literature state that SDI_{15} is not sufficiently accurate to predict the fouling ability of water. For instance, the deterioration of RO has been observed even when $SDI_{15} < 1$ [4], and no clear correlation between the performance of RO and the level of SDI_{15} has been found in an experiment using water with fouling matter added [5]. These study results lead us to examine the performance of SDI_{15} under a variety of conditions to create a more reliable and feasible index of the fouling potential of water. We examined 187 samples of seawater taken under various environmental conditions and conducted filtration experiments. Of these, 72 samples were raw water, 30 samples were dual media filtration seawater, 52 samples were micro filtration (MF) seawater, and 33 samples were coarsely filtered seawater. The temperature (℃), electric conductivity (EC), pH, ultraviolet absorption at 260 nm (E260), turbidity, and volume of water treated were measured every 5 seconds. The SDI_{15} was obtained for each sample after the experiment. The capacity of the experimental apparatus allowed for a maximum of 12,000 ml of water to be measured. A summary of our experiment is shown in Table 1, where V_{15} denotes the total amount of water filtered (ml) in 15 minutes. The apparatus capacity prevented V_{15} measurements of 39 samples. Figure 1 shows a scatter plot of SDI_{15} versus V_{15}. If SDI_{15} reflects precisely the trend in permeability due to fouling from the beginning to the end of the experiment, SDI_{15} and V_{15} should be closely related to each other. V_{15} varied considerably, even when $SDI_{15} < 4$; V_{15} varied from 6,000 ml to over 12,000 ml when $SDI_{15} < 5$. The results suggest that SDI_{15} does not necessarily represent the fouling condition of water, even when SDI_{15} is within a limit normally required by RO manufactures.

Table 1: Summary of the experiment

	Sample	Avg	Max	Min	SD
SDI_{15}	187	4.74	6.51	1.83	1.24
EC	150	50.06	58.30	43.00	1.89
pH	153	8.08	8.70	6.19	0.47
E260	157	0.33	45.50	0.00	3.63
Turbidity	161	0.44	11.60	0.01	1.04
Temperature	146	20.54	29.00	9.70	4.82
V_{15}	148	6582	11728	1143	2594

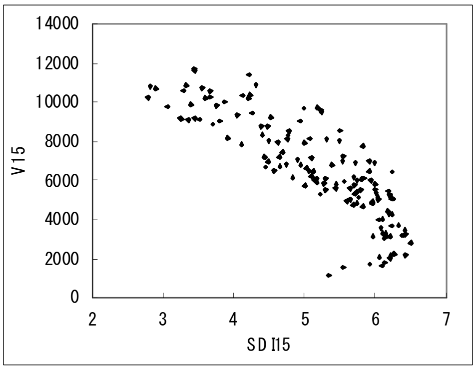

Figure 1: Scatter plot of SDI_{15} versus V_{15}

3. Statistical Analysis and New Fouling Index

Ideally, no RO membrane deterioration occurs when the water contains no foulant. Therefore, V_t should be proportional to the elapsed time, that is, $V = aT$, where a is determined by the experimental and environmental conditions. Taking the logarithm, we have $\log V = \log a + \log T$. This indicates that when the water contains no foulant, $\log V$ and $\log T$ should have a linear relationship with a slope of 1. Before proceeding to a statistical analysis of the samples, four of them were selected randomly and investigated in detail for specific phenomena associated with fouling. Figure 2 (left) shows relationships between V and T, and Figure 2 (right) shows their log-log relationships.

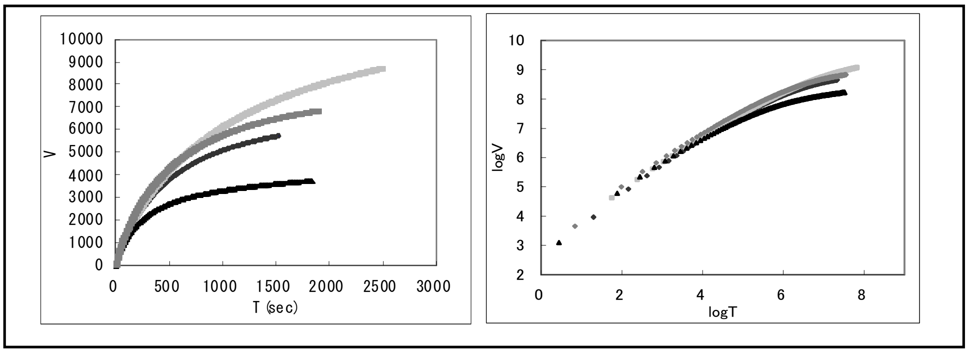

Figure 2: Elapsed time (T) vs cumulative filtrate (V) for four samples (left), and log-log relationship of the four samples (right)

In Figure 2 (right), the difference in V_{15} between samples was small up to about $\log T = 4.1$, or 60 seconds, and then expanded drastically. These findings prompted us to divide the data into Phase 1 for the first 60 seconds, or $\log T < 4.1$, and Phase 2 for the rest of the test period. We then applied a piecewise linear regression model [6]:

$$\log V = \alpha + \beta \log T + \gamma < \log T - 4.1 > + \varepsilon \tag{2}$$

where $< \log T - 4.1 > = \mathrm{Max}\{0, \log T - 4.1\}$ is a piecewise linear function with one change point at $\log T = 4.1$, and ε represents random variables that independently follow a normal distribution $N(0,\sigma^2)$. The results are shown in Table 2. The P-values for γ were all highly significant, indicating that dividing the time into two phases was more efficient than using one linear regression model for the whole period. We considered Phase 1 to show the permeate flow rate in a state where the fouling effects were relatively negligible; the approximately linear straight lines indicated that the water velocity depended upon the environmental and experimental conditions. Phase 2 showed the permeate flow rates after 1 minute had elapsed, where the effects of the foulant dominated. Thus, we applied the linear regression model

$$\log V = \alpha + \beta \log T \tag{3}$$

to Phase 2 and defined the regression coefficient β as the "permeation coefficient" ($\beta \le 1$). Note that α depends on the results of Phase 1, or more exactly, the value of $\log V$ at $T = 60$, but β does not. Furthermore, we assumed the effect of an environmental factor was multiplicative by a factor A through the study period. Thus, $V = e^{\alpha}T^{\beta}$ was modified to $V = Ae^{\alpha}T^{\beta}$, or

$$\log V = \log A + \alpha + \beta \log T \tag{4}$$

That is, the factor affected α but not β in (3).

Table 2: Results of piecewise linear regression analysis

	β (P-value)	γ (P-value)
Sample1	1.10 (<0.0001)	-0.55 (<0.0001)
Sample2	1.11 (<0.0001)	-0.54 (<0.0001)
Sample3	1.07 (<0.0001)	-0.69 (<0.0001)
Sample4	1.10 (<0.0001)	-0.60 (<0.0001)

4. Device Dependency of Fouling Index

It is preferable that the fouling index is not influenced by the measurement devices. However, some reports show that SDI_{15} is significantly influenced by measurement devices, such as filter holders, when the experimental water is nearly purified [7, 8]. Thus, we also conducted an experiment to examine the effects of the filter holders on V_{15}, SDI_{15}, β, and α in (3). Three different holders (0: Advantec KS-47; 1: Millipore XX4304700; 2: Millipore XX4404700) and three different samples (0: raw water; 1: MF filtered water; 2: MF filtered water on the next day) were used. The results are tabulated in Table 3. ANOVA was applied to the data to obtain the results shown in Table 4.

Table 3: Results for each combination of holders and samples

No	Sample	Holder	V_{15}	SDI_{15}	β	α
1	1	0	4093	6.46	0.44	5.44
2	1	1	4547	6.48	0.45	5.45
3	1	2	3380	6.42	0.43	5.28
4	2	0	9593	4.65	0.74	4.15
5	2	1	10585	4.47	0.76	4.11
6	2	2	8537	4.41	0.77	3.85
7	3	0	11011	3.96	0.80	3.86
8	3	1	12385	3.92	0.81	3.97
9	3	2	10044	3.96	0.80	3.78

Table 4: P-values by ANOVA

	Samples	Holders
V_{15}	<0.0001	0.006
SDI_{15}	<0.0001	0.342
β	<0.0001	0.421
α	<0.0001	0.023

Different samples had significantly different effects on all items. As the difference in holders had significant effects on V_{15} and α,

V_{15} and α are not appropriate for a fouling index. The result that α, but not β, depended on the holders can be explained by considering (4) in Section 3.

5. Optimum choice of T for β_T

As the permeation coefficient β may be defined for a filtering experiment lasting less than 15 minutes, we reanalyzed the data to determine the optimum choice of T for β_T, that is, to obtain the smallest T without sacrificing accuracy. We applied the linear regression model (2) to the data censored at T for $T = 2, 3, \ldots, 15$. The results are tabulated in Table 5.

Table 5: Results of linear regression analysis for optimum choice of β_T

	β_2	β_3	β_4	β_5	β_6	β_7	β_8
R^2	0.74	0.77	0.79	0.81	0.82	0.83	0.83
SE	1313	1236	1177	1134	1103	1083	1071
	β_9	β_{10}	β_{11}	β_{12}	β_{13}	β_{14}	β_{15}
R^2	0.83	0.83	0.83	0.83	0.83	0.82	0.82
SE	1065	1064	1068	1074	1083	1094	1106

The value of T that maximized the coefficient of determination R^2 and minimized the standard error (SE) was 9 or 10. Because a smaller T is preferable, we regarded $T = 9$ as the optimum choice. $T = 9$ is approximately half the time required to determine SDI_{15}.

6. Comparison of β_9 and SDI_{15}

The same experimental apparatus was used for all 187 samples described in Section 2, and therefore we may assume that the larger V_{15} is, the smaller the fouling potential of the water becomes. We obtained a scatter plot for β_9 versus V_{15} (Figure 3 (right)) and for SDI_{15} versus V_{15} (Figure 3 (left)) to assess the degree of association. Both the coefficient of determination R^2 and the standard error of the residuals indicated that β_9 was superior to SDI_{15} when predicting V_{15}.

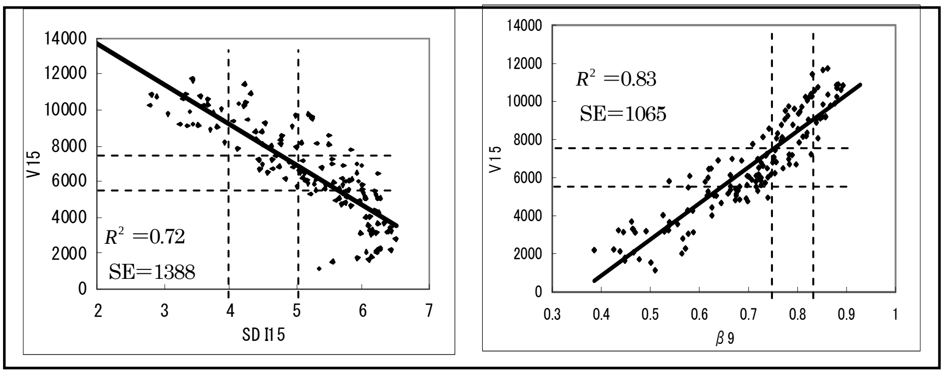

Figure 3: Scatter plot for SDI_{15} versus V_{15} (left) and β_9 versus V_{15} (right)

Finally, we need to determine a reference value of β_9 corresponding to $SDI_{15} < 4$ or $SDI_{15} < 5$ in view of the fact that SDI_{15} is currently the most widely used fouling index. Figure 3 shows that V_{15} was greater than 8,000 ml when $SDI_{15} < 4$ and was approximately greater than 6,000 ml when $SDI_{15} < 5$. The range of β_9 that almost filled $SDI_{15} < 4$ or $SDI_{15} < 5$ was $\beta_9 > 0.83$ or $\beta_9 > 0.75$, respectively.

7. Conclusion

A number of studies have investigated the influence of the physicochemical aspects of foulant on the values of the SDI in well-controlled experiments, but only a few studies have describe the performance of the SDI under natural environmental conditions from a statistical point of view [9]. We conducted two experiments to statistically examine the performance of the SDI and defined a new fouling index β termed a "permeation coefficient." The results can be summarized as follows.

1. V_{15}, the amount of filtrate sampled in 15 minutes, had a significant dependence on the experimental apparatus.
2. The relationship between $\log T$ and $\log V$ was approximately linear in water with less foulant.

3. Dividing the time interval into two phases, Phase 1 (before 60 seconds) and Phase 2 (after 60 seconds), significantly improved our ability to fit a linear model to log$V$ versus log$T$.
4. The permeation coefficient β was defined as the regression coefficient of a linear regression model applied to the Phase 2 data.
5. Neither β nor SDI_{15} significantly depended on the experimental apparatus.
6. β_T denoted the permeation coefficient obtained from censoring the data after T minutes.
7. The optimum choice of T was T = 9 in our experiment. The time required to determine β_9 was approximately half that required to determine SDI_{15}.
8. β_9 was a more reliable and feasible measure of fouling than SDI_{15}.
9. $\beta_9 > 0.83$ and $\beta_9 > 0.75$ corresponded to $SDI_{15} < 4$ and $SDI_{15} < 5$, respectively, in our experiment.

As the desalination industry is highly conservative, adoption of a new fouling index would require further field-testing, as well as experiments or theory to confirm our findings based on physical or chemical points of view.

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