A Fouling Index Reflecting Statistical Aspects of Fouling Process with Reverse Osmosis Desalination

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***Abstract*—Reverse osmosis membrane (RO) is becoming a most popular instrument to desalinate seawater as a result of new developments in membrane technology. The critical factor governing successful long-term reverse osmosis (RO) in desalination plants is *fouling* caused by the turbidity of seawater, such as by suspended solids, sparingly soluble salts, or biological growth. To reduce the turbidity, the seawater is first treated with sand, film, or other agents, resulting in what is called "pretreated seawater" for RO. The fouling potential of this pretreated seawater should be assessed quickly and accurately to maintain RO performance.**

Silt density index (SDI) is a widely used standard measure of the fouling potential of the pre-treated seawater on a membrane surface, and judging whether it should be supplied with the value of SDI is usually performed. However, some literatures indicate that SDI does not always correctly represent the fouling potential. Thus, in this study, we sampled seawater under various environmental conditions, such as a place, a season, turbidity, pH, and water temperature, and conducted filtering experiments. Statistically analyzing the relationships between the amount of filtrated water, elapsed time, and environmental factors, we developed a new fouling potential index, termed "*permeation index* β."

Comparing performance between SDI and PI, we showed the predominance of the latter.

***Index Terms*— SDI$_{15}$, permeation index β, fouling**

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Ⅰ. Introduction

In the desalination plant, the sea water is first treated by sand, film, or others to reduce the turbidity. Then, the pre-treated seawater is supplied to RO membrane to obtain pure water. RO membrane is expensive and is deteriorated as time passes. It is critical to determine when to change RO membrane. When it is exchanged too early, the running cost of the plant is raised. On the other hand, when the exchange timing is delayed, the amount and the quality of pure water decreases, that will lead to the serious effect on the plant management. To determine the best possible timing for the exchange, the fouling potential of the pretreated seawater should be evaluated accurately.

The most commonly used fouling index is the silt density index (SDI), defined by:

$$SDI_T = \frac{\left(1-{}^{t_i}\!/_{t_f}\right)?\ 00}{T} \qquad (1)$$

where T is normally 5 or 15 min, the time t_i required for collecting the initial 500ml of filtrate is measured. After T min of filtration, the time t_f required for finally collecting 500ml of filtrate is also measured [1]. Although some RO maker requires $SDI_{15} \leqq 4$ or $SDI_{15}<5$ for water to be supplied to RO, deterioration of RO was observed even when $SDI_{15}<1$ [2] and in an experiment using water added fouling matter, no clear correlation between the performance of RO and the level of SDI_{15} was found [3]. A number of literatures discuss that SDI_{15} does not have enough accuracy as predicting the fouling ability of water [4], [5].

Considering that the SDI may not be able to reflect the true fouling potential of seawater, the modified fouling index (MFI) was created based on a physiochemical analysis of an experimental filter. However it became apparent that the MFI depends upon the pressure in the filtration experiment [6], to determine the MFI value was not accurate when organic matter was a major foulant [7], and the MFI was not sufficiently reproducible [6], because small measurement errors seriously affected the MFI values. On the other hand, it is widely accepted that SDI_{15} values depend little on environmental or experimental conditions, yet it is not as fully accepted as a reliable index as previously described. These considerations lead us to experiments to examine the performance of SDI_{15} under a variety of conditions and to create a more reliable and generally applicable index of the fouling potential of water.

II. Experimental Methods

We examined 187 samples of seawater taken under various environmental conditions, including location, season, turbidity, pH, and water temperature, and conducted filtration experiments. 72 samples were seawater, 30 DMF filtered seawater, 52 micro filtered(MF) seawater, and 33 per-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 12,000ml of water to be measured.

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
NTU	99	0.23	1.19	0.06	0.21
V_{15}	148	6582	11728	1143	2594

III. Performance of SDI_{15}

Summary of the experiment is tabulated In Table.1, where V_{15} denotes the total amount of water filtered in 15-minutes. The apparatus capacity prevented V_{15} recording of 32 samples. If SDI_{15} reflects the trend in permeability due to the fouling from the beginning to the end of the experiment, SDI_{15} and V_{15} should be closely related with each other. Fig. 1 shows the scatter plot of SDI_{15} vs. V_{15}. V_{15} varies between 8,000~12,000ml even when $SDI_{15} \leqq 4$ and 6,000~12,000ml 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 makers.

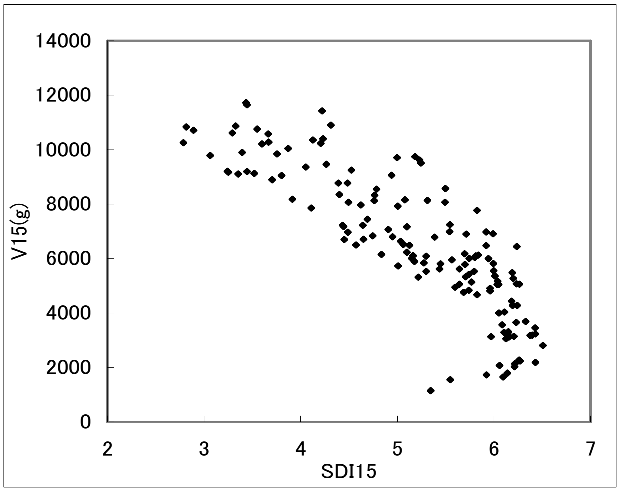

Fig. 1 : The scatter plot of SDI_{15} vs. V_{15}

IV. Analysis of Data and New Fouling Index

Ideally, no deterioration occurs with water with no foulant, therefore V_t should be proportional to the time elapsed, that is, V= T, where is determined by the experimental and environmental conditions. Taking logarithm, we have logV=log α+logT. This indicates that when the water contains no foulant, logV and logT should have a linear relationship with slope *1*; consequently, we can obtain a scatter plot of logV vs. logT using all our samples. Before proceeding to the statistical analysis of the samples, four of them were selected randomly and investigated in detail for specific phenomena associated with fouling. Fig. 2(a) shows the original relationship and Fig. 2(b) shows the log-log relationship.

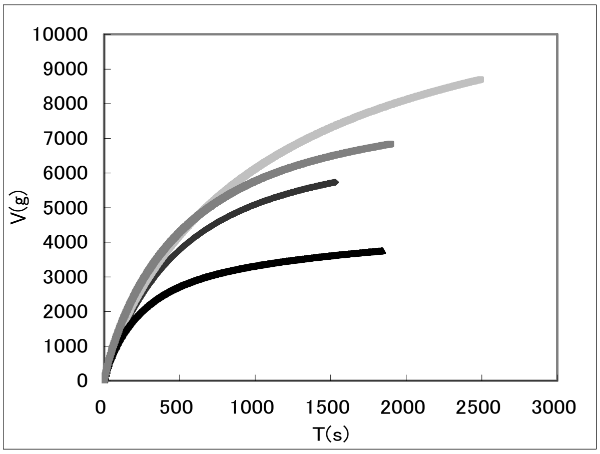

Fig. 2(a) : The original relationship for the four samples

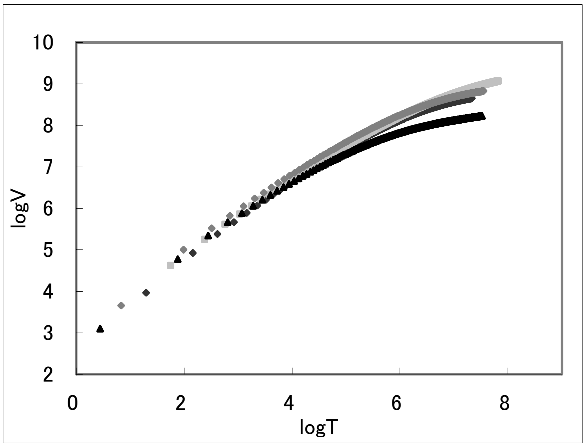

Fig. 2(b) : The log-log relationship for the four samples

In Fig. 2(b), the difference in V_{15} between samples is small up to about 4.1, or 60 seconds, then expands drastically. These findings prompted us to divide the data into Phase 1 for the first 60 seconds, or logT<4.1 and Phase 2 for the rest of the period. Then, we applied the piecewise linear regression model [8]:

$$\log V=\alpha+\beta\log T+\gamma\langle\log T-4.1\rangle+\varepsilon$$

where $\langle\log T-4.1\rangle=\mathrm{Max}\{0,\log T-4.1\}$ is a linear function with one change point at logT=4.1, and ε's are random variables independently following a normal distribution $N(0,\sigma^2)$. The results are shown in Table. 2. The P-values for γ are all highly significant, indicating that dividing the time into the two phases is more efficient than using one linear regression model for the whole time interval. We considered Phase 1 to show the permeate flow rate in a state where the fouling effects are relatively negligible and the approximately linear straight lines reflect water velocity that depends upon the environmental and experimental conditions. Phase 2 shows the permeate flow rates after 1 minute has elapsed where the effects of the foulant dominate.

Thus, we applied a linear regression model

$$\log V=\alpha+\beta\log T \qquad (2)$$

to Phase 2 and define the regression coefficient β as the "*permeation index*" ($\beta \leq 1$). Note that α depends on the results of Phase 1, or more exactly the value of logV at T=60, but β does not. Furthermore, assume the effect of an environmental factor is multiplicative by a factor "A" through a study period, then $V=e^{\alpha}T^{\beta}$ is modified to $V=Ae^{\alpha}T^{\beta}$, or

$$\log V=\log A+\alpha+\beta\log T \qquad (3)$$

That is the factor affects α but not β in (2).

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)

V. Device Dependency of Fouling Index

It is preferable that the fouling index not be 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 [6], [9]. Thus, we also conducted an experiment to examine the effects of the filter holders on SDI_{15}, MFI, β ,and α respectively in (2).

Three different holders (0:Advantec KS-47; 1:Millipore XX4304700; 2:Millipore XX4404700) and three different samples (0: seawater; 1: micro filtration(MF) filtered water; 2 : micro filtration(MF) filtered water on the next day) were used. The results are tabulated in Table. 3.

Table. 3 : Results for each combination of holders and samples

No	Sample	Holder	SDI_{15}	MFI	β	α
1	0	0	6.46	46.68	0.44	5.44
2	0	1	6.48	36.23	0.45	5.45
3	0	2	6.42	69.08	0.43	5.28
4	1	0	4.65	5.21	0.74	4.15
5	1	1	4.47	3.99	0.76	4.11
6	1	2	4.41	6.05	0.77	3.85
7	2	0	3.96	3.15	0.80	3.86
8	2	1	3.92	2.50	0.81	3.97
9	2	2	3.96	3.85	0.80	3.78

Since the MFI values of Sample0 are extremely large as compared to the others, we used log-transformed values of them (Table. 4). ANOVA was applied to the data to obtain the results shown in Table. 5.

Table. 4 : logMFI values

	Holder0	Holder1	Holder2
Sample0	3.84	3.59	4.24
Sample1	1.65	1.38	1.80
Sample2	1.15	0.92	1.35

Table. 5 : P-value by ANOVA

	Waters	Holders
SDI_{15}	<0.0001	0.342
logMFI	<0.0001	0.003
	<0.0001	0.421
	<0.0001	0.023

Different waters had significant effects on all items, whereas the difference of holders had significant effects only on MFI and α. Both no significant association between β and the holders and the significant association between α and the holders can be explained by the consideration with (3) in Section Ⅳ.

To further examine the dependence of α on environmental factors, we applied a multiple liner regression analysis to 91 samples with no missing values. The results shown in Table.6 suggest that each environmental factor significantly affects α.

Table. 6 : Results of the multiple regression analysis

Factor	Estimate (p-value)	Factor	Estimate (p-value)
Intercept	16.7 (<0.0001)	E260	4.17 (<0.0001)
logEC	-2.63 (<0.0001)	logTurbidity	0.149 (<0.0001)
logpH	-1.49 (0.0002)	logTemp	0.267 (0.0018)

VI. Comparison of and SDI_{15}

The same experimental apparatus was used for all 187 waters described in section Ⅱ, and therefore we may assume that the larger the V_{15}, the smaller the fouling potential of water. Thus, we obtained a scatter plot for vs. V_{15} (Fig. 3(a)) and for SDI_{15} vs. V_{15} (Fig. 3(b)) to compare the degree of associations. Both coefficients of determination R^2 and the standard error of residuals indicate is superior to SDI_{15} in predicting V_{15}.

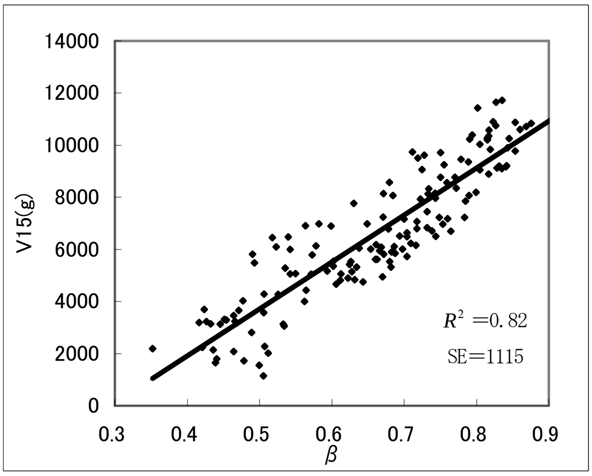

Fig. 3(a) : The scatter plot for vs. V_{15}

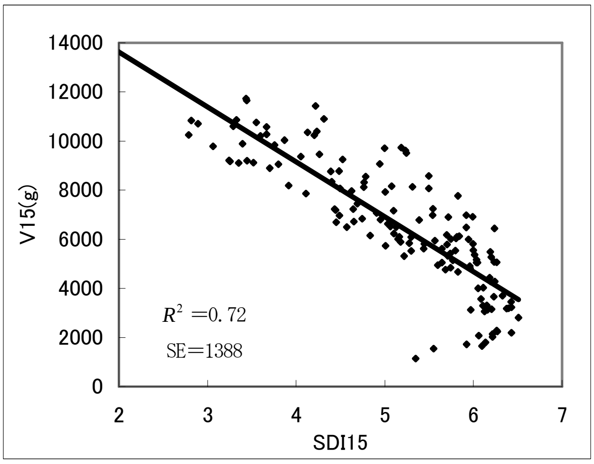

Fig. 3(b) : The scatter plot for SDI_{15} vs. V_{15}

Finally, we need to determine a reference value of corresponding to $SDI_{15} \leqq 4$ or $SDI_{15} < 5$ in view of the fact that currently SDI_{15} is the most widely used fouling index.

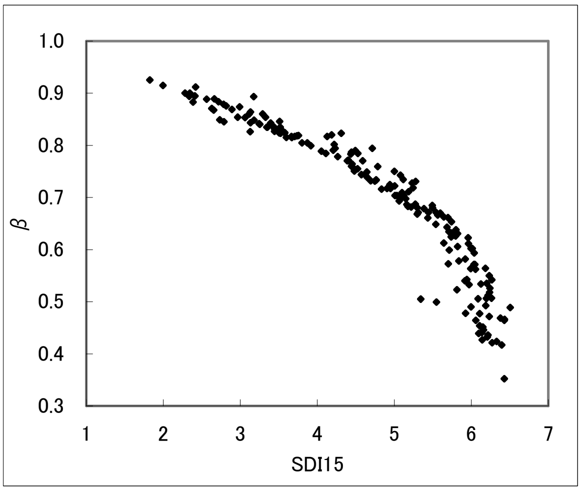

Fig. 4 : The scatter plot for vs. SDI_{15}

Fig. 4 shows a scatter plot for vs. SDI_{15} using all samples. The range of that almost fills $SDI_{15} \leqq 4$ or $SDI_{15} < 5$ is $\geqq$ 0.83 or >0.75, respectively. Fig. 3(a) and Fig. 3(b) suggest that V_{15} is distributed between 8,000~12,000ml when $SDI_{15} \leqq 4$ but between 9,000~12,000ml when $\geqq$0.83. On the other hand, V_{15} is distributed between 6,000～12,000ml when $SDI_{15} < 5$ but between 7,000～12,000ml when ＞0.75. These results suggest that $\geqq$0.83 or >0.75 would be a better reference value for fouling with higher accuracy than $SDI_{15} \leqq 4$ or $SDI_{15} < 5$, respectively.

Ⅳ. Conclusion

Statistically analyzing the results of the two experiments, we have found that the permeability of water in Phase 1, or the first 60 seconds, is mainly dominated by the velocity of water, the water quality, environmental conditions, and the characteristics of the experimental apparatus, such as filter holders. On the other hand, in Phase 2, or after 60 seconds to 15 minutes, permeability is mainly dominated by the fouling ability of water. Based on these findings, we proposed a new fouling index β, termed *permeation index*, as the regression coefficient of the linear regression model between logV and logT in Phase 2. Comparing the performance of β and SDI_{15}, we proposed $\beta \geqq 0.83$ as a reference value corresponding to $SDI_{15} \leqq 4$ and it was revealed that the former provided more accurate information on fouling than the latter in our experiment. Challenging problems for future study would determine the most appropriate time to divide Phase 1 and Phase 2 and to study the relative merit of β to SDI_{15} at the actual plant operation as well as in controlled experiments.

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