Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.912162

54 (2015) 973–978
April

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Evaluation of ceramic membrane applications for water treatment plants with a life cycle cost analysis

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Received 15 January 2014; Accepted 2 April 2014

ABSTRACT

Ceramic membranes have many advantages such as durability, chemical resistance, high flux, and long life span. However, they generally require relatively high initial investment cost compared to polymeric membranes when they are used for a water treatment process. Therefore, if ceramic membranes are considered to be applied to a water treatment plant (WTP), the life cycle cost (LCC) analysis should be performed to evaluate its economic feasibility. In this study, the capital and operational expense data of selected WTPs which have membrane filtration processes were used for their LCC analysis. Production capacity of the plants, membrane flux and life span, and costs of membrane modules and electricity were considered as key analysis factors. From the LCC analyses with various conditions including membrane costs and membrane flux, the correlation of the key design parameters was obtained that can make the ceramic membrane filtration more cost-effective compared to the polymeric membrane method. At present state, WTP with a ceramic membrane should increase the permeate flux to meet the economic feasibility, but it is expected to have a bright future because of the recent development of manufacturing technologies and increase of demand in many industries.

Keywords: Treatment; Ceramic membrane; Life cycle cost (LCC); Water treatment plant design

1. Introduction

Recently in Korea, a water treatment plant (WTP) using a ceramic membrane filtration technology was constructed and started its operation in 2013. Generally, ceramic membranes have good mechanical strength, strong durability against harsh chemical cleaning process, applicability to hot environment and to slurries containing hard suspended solids, and durability against biological corrosion, compared to

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Presented at the 6th International Conference on the "Challenges in Environmental Science and Engineering" (CESE-2013), 29 October–2 November 2013, Daegu, Korea

1944-3994/1944-3986

polymeric membranes [1–2]. Those resulted in wide use of ceramic membranes in many industrial plants [3]. Ceramic membranes have been used for solid–liquid separation in various fields such as chemical, pharmaceutical, food, semiconductor, and textile industries as well as water treatment industry [2,4,5]. When it comes to water treatment industry, ceramic membranes are being used for treatment of the oilfield produced water generated from oil tank dewatering, the backwash water from WTPs, and the secondary effluents of wastewater treatment plants [6–11]. In China, ceramic membranes were tried as a pretreatment process for a desalination pilot plant [12,13]. The advantages mentioned above enable the ceramic membrane filtration process to be combined with other pretreatment processes flexibly and to be operated at broad range of environmental conditions. It becomes a big advantage at the operating stage.

Japan has the most references of public WTPs using ceramic membrane filtration process. Microfiltration membranes were used for the water treatment mostly. Japan has 117 public WTPs which use the ceramic membranes with equivalent capacity of 547,300 m^3/d as of 2012 [3]. In Korea, a WTP (with 16,000 m^3/d production capacity) using the ceramic microfiltration process was first constructed and then operated in February 2013. The original plant which was built in 1979 was retrofitted with pre-ozonation, ceramic membrane filtration, and granular activated carbon processes for the effective removal of taste and odor, dissolved organics, disinfection byproducts, and manganese [3].

Ceramic membranes filtration process could be operated with higher flux than polymeric membranes' due to their higher porosity and more hydrophilic surface [7]. The resistance of ceramic membranes against thermal, mechanical, and chemical stress allows a better recovery of membrane performance from fouling. For example, NGK uses 5.0 bar of pressure for backwashing and it results in a good backwash efficiency and higher operation flux consequently. When it comes to the ceramic membranes' life time, it is reported to last its function for 10–20 years, which is generally twice longer than that of polymeric membranes [7,14].

Despite above advantages of ceramic membranes, they have some disadvantages. Different thermal expansion of ceramic membrane and the module housing may cause problems with sealing. Therefore, an installation engineer needs to choose an appropriate gasket [15]. Also, ceramic membranes are brittle that they need to be handled carefully. The biggest disadvantage of ceramic membrane is the high price so far. Ceramic membranes are more expensive than polymeric membranes with respect to the membrane area. The prices of ceramic membranes are different by module types and pore sizes [7]. Thus, design engineers should consider the advantages of ceramic membranes critically at the planning stage before applying them to a real practice [16]. The known advantages such as a long life span could be different depending on its manufacturers and module types.

This study investigated the economic feasibility of ceramic membranes for WTPs by comparing the life cycle costs (LCCs) with polymeric membranes. The researchers intended that this study could provide an objective methodology that can help engineers to decide which type of membrane is more economic at their planning stage.

2. Methods

2.1. Data collection

The LCC analysis needs reliable data-sets of construction (capital) and operation costs for existing WTPs. In this study, the cost data-sets were obtained from eight WTPs using membrane filtrations in Korea as shown in Table 1 [17,18]. The earliest WTP using membrane was installed in 2003. Both submerged and pressurized types of polymeric membranes were used in seven of eight WTPs. So far, there is only one WTP using ceramic membrane filtration in Korea. The capital and operation costs are divided into following two categories: (1) the capital costs of membrane module, membrane skid, civil works, architecture, mechanical works, landscape, electrical works, and instrument/control; and (2) the operation cost of electricity, chemicals, maintenance, and membrane replacement.

2.2. Capital cost analysis

Fig. 1 shows the categories of construction costs with their portions in the total capital cost. The portions are obtained by averaging the collected data of WTPs in Table 1. The portion of ceramic membrane module is almost twice higher than that of polymeric membrane, which implies the cost of membrane module is higher in the case of ceramic than polymeric membrane. Except for membrane module, the portion of each category is site-specific. Thus, the portion for membrane module is the key parameter to determine the LCC of WTP.

2.3. Operation cost analysis

Fig. 2 shows the categories of operational costs with their portions in the total operational cost. The

Table 1
The WTPs using membrane filtration in Korea

WTP		Installation year	Capacity (m^3/d)	Membrane type	Capital cost (USD)	Operation cost (USD)
Polymeric membrane	A	2003	3,600	MF(UF)/Pressure	2,389,000	400,000
	B	2005	1,000	UF/Pressure	N.A.	15,800
	C	2009	30,000	MF/Pressure	31,545,000	927,600
	D	2011	25,000	MF/Submerged	5,090,000	334,900
	E	2011	25,000	MF/Pressure	5,181,000	N.A.
	F	2011	10,000	MF/Pressure	N.A.	146,900
	G	2012	6,000	MF/Submerged	N.A.	219,500
Ceramic membrane	H	2012	16,000	MF /Pressure	10,293,000	N.A.

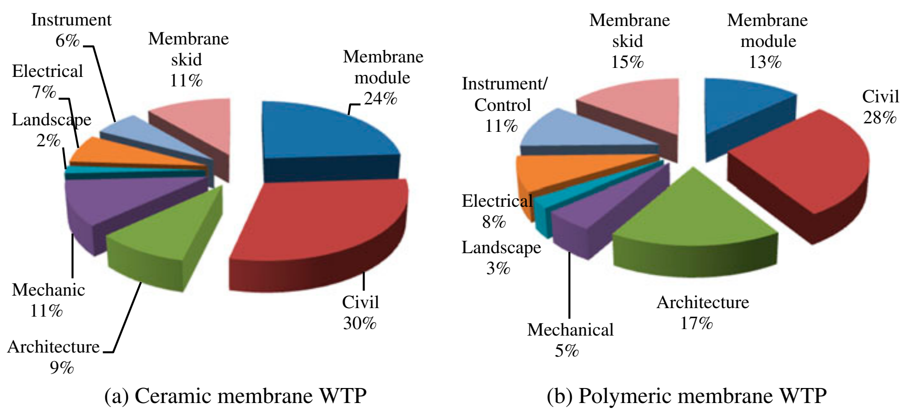

Fig. 1. Capital costs for WTPs.

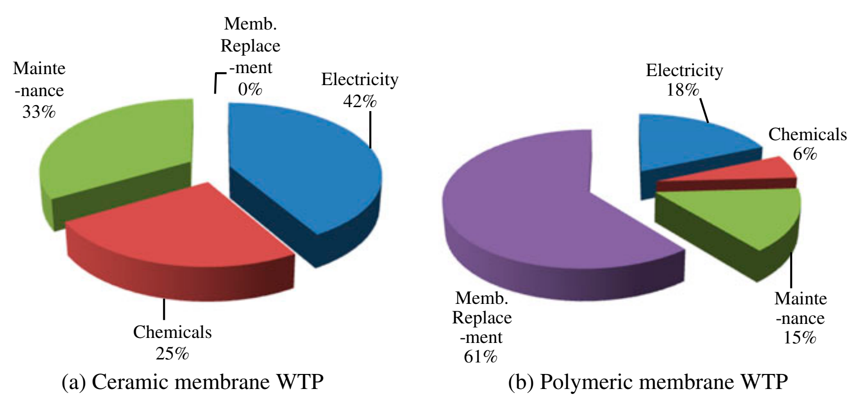

Fig. 2. Operational costs for WTPs.

portions in the case of polymeric membrane are obtained by averaging the collected data of the WTPs in Table 1, but those in the case of ceramic membrane are produced (due to lack of data) based on three assumptions: (1) ceramic membrane is not replaced during the life time of WTP; (2) the chemicals cost for ceramic membrane is twice as high as that for polymeric membrane; and (3) the electricity cost per unit water production of both ceramic and polymeric membranes are identical. The first assumption is acceptable due to the robust characteristics of ceramic membrane and the second one is also acceptable because highly concentrated chemicals for cleaning, coagulation, and oxidation may be applied to WTP using ceramic membrane filtration to maintain higher membrane flux than that of polymeric membrane.

2.4. LCC analysis

The objective of the LCC analysis in this study is to determine a membrane material type for a WTP by comparing the LCC values of the case using ceramic membrane filtration with that using polymeric membrane filtration. The LCC can be expressed as water production cost per unit volume, which has contributions from capital (C, USD/m^3) and operation costs (O, USD/year), and yearly interest rate (r) depicted as:

$$\mathrm{LCC} = \frac{C[r + r/\{(1+r)^n - 1\}] + O}{365Q} \tag{1}$$

where Q and n are the capacity (m^3/d) and the life time of WTP, respectively. The capital cost can be calculated using the equations below:

$$C = C_m + \sum C_{\text{others}} = C_m/P_m \tag{2a}$$

$$C_m = C_{u,m}A_m = C_{u,m}Q/J \tag{2b}$$

where C_m and C_{others} are capital cost contributed by membrane and other categories, respectively; P_m, $C_{u,m}$, A_m, and J are the portion of the total capital cost, the unit cost per membrane area, and membrane module flux, respectively. P_m values for ceramic and polymeric membranes are 0.24 and 0.13, respectively. The operation cost can be determined from the following equations:

$$O = O_e + \sum O_{\text{others}} = O_e/P_e \tag{3a}$$

$$O_e = O_{u,e}Q \tag{3b}$$

where O_e and O_{others} are the operation costs contributed by electricity and other categories, respectively; and P_e and $O_{u,e}$ are the portions of the total operation cost and the unit electricity cost per production volume, respectively. P_e values of ceramic and polymeric membranes are 0.415 and 0.185, respectively, which means that the total operation cost of WTP using ceramic membrane filtration is smaller than that using polymeric membrane filtration. Table 2 shows an example of input values for the LCC analysis in this study.

3. Results and discussion

3.1. Expected costs for construction and operation of a WTP

Tables 3 and 4 show the analysis result of expected costs for the construction and operation of WTPs (30,000 m^3/d, production capacity) with ceramic and polymeric membranes. The capital cost of a ceramic membrane WTP is evaluated to be 32,634,000 USD and it is 16% larger than that of polymeric membrane WTP. The yearly operational cost is 562,717 USD for polymeric membrane WTP, and it is 2.5 times larger than that for ceramic membrane WTP. The replacement cost for polymeric membranes contributes around 60% of total cost for 20 years of operation.

3.2. LCC of water

Fig. 3 shows the analysis results of LCC of membrane filtration WTPs considering the construction cost, operational cost, discount rate, and the life span. The water production costs obtained by the LCC analysis are 0.28 USD from the ceramic membrane WTP and 0.274 USD from the polymeric membrane WTP. Among them, 0.020 USD is contributed by the operation cost of the ceramic membrane WTP, and 0.051 USD is contributed by one of the polymeric membrane WTP. This indicates that 93% of the water production cost of the ceramic membrane WTP is contributed by its capital cost and the operation cost contributes 7%

Table 2
Input values for the LCC analysis

	Flux (m/d)	Membrane module cost (1 USD/m^2)	Electricity cost (0.001 USD/m^3)	Capacity (m^3/d)	Interest rate	Life time (years)
Ceramic membrane	2.3	600	9.5	30,000	0.06	20
Polymeric membrane	1	120	9.5			

Table 3
Capital costs for a WTP with membrane filtration process ($30,000\ m^3/d$, production capacity, unit: 1,000 USD)

Construction categories	Ceramic membrane	Polymeric membrane
Membrane module	7,826	3,600
Membrane skid	3,655	4,118
Instrument/control	1,952	2,985
Civil works	9,721	7,905
Mechanical works	3,587	1,453
Electrical works	2,221	2,379
Architecture	3,077	4,867
Landscape	593	713
Sum	32,634	28,019

Table 4
Yearly operation expenses for a WTP with membrane filtration process ($30,000\ m^3/d$, production capacity, unit: USD)

Operational categories	Ceramic membrane	Polymeric membrane
Membrane replacement	–	342,923
Electricity	104,025	104,025
Chemicals	62,977	31,701
Maintenance	50,722	84,068
Sum	217,725	562,717

of the total cost. As for the polymeric membrane WTP, 82% of the water production cost is contributed by its capital cost and 19% is contributed by its operational cost as shown in Fig. 3.

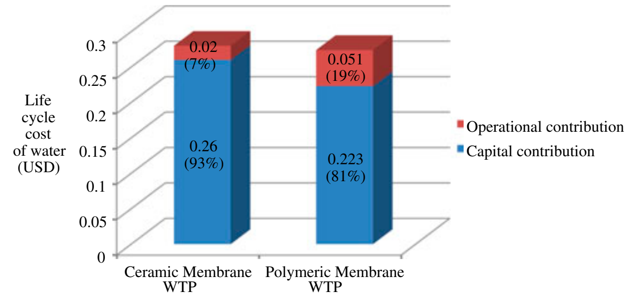

Fig. 3. LCC of produced water from ceramic and polymeric WTPs.

The LCC of water can be simulated using input values for flux, membrane module price, electricity cost, capacity, discount rate, and life span. Then, the flux value was adjusted from 1.0 to 3.0 m/d, and the membrane module price was also adjusted from 200 USD to 600 USD. The LCCs of produced water from WTPs are shown in Fig. 4, which can be used to compare the economic feasibility of ceramic membrane to polymeric membrane. If a designer or planner of WTP is considering ceramic membrane with 2.0 m/d flux, the price of ceramic membrane module should be less than 510 USD/m^2. It means that the ceramic membrane could be economically feasible if its cost is less than 4.25 times of polymeric membrane's (120 USD). If the flux is 1.5 m/d, the price of ceramic membrane module should be less than 390 USD (or 3.25 times of polymeric membrane module's price) to be economically comparable to the polymeric membrane.

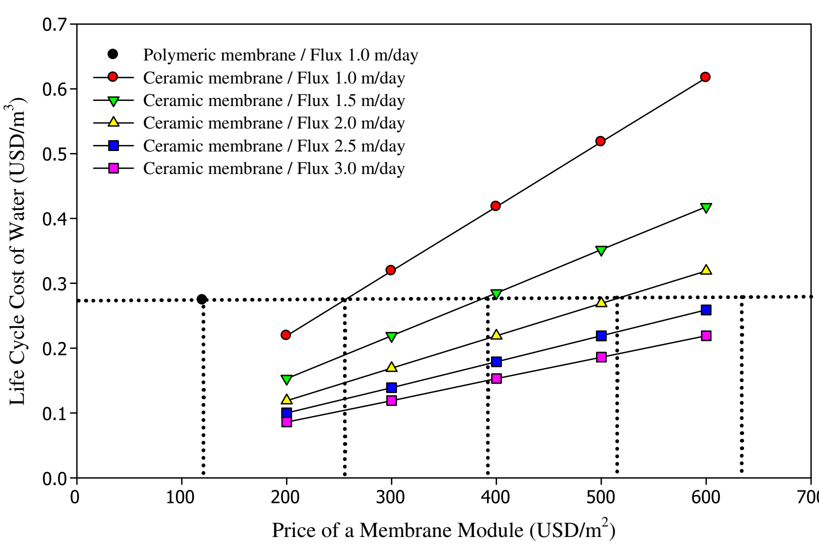

Fig. 4. LCC analysis for different flux and membrane module price.

4. Conclusions

The present study investigated the LCC of WTPs with ceramic or polymeric membranes. For the analysis, construction and operation cost data of WTPs were collected to the best way. The researchers tried to reflect factors affecting the price of water as many as possible, and the LCCs of water were evaluated considering capital and operation expenses, life span and discount rate, and membrane module price, and flux. The evaluated LCCs of water from the ceramic and polymeric membrane WTPs are comparable, 0.28 USD and 0.274 USD, but operational contributions to the prices are 7 and 19%, respectively. From the LCC analyses, the correlation of the key design parameters were obtained to make the ceramic membrane filtration more cost-effective compared to the polymeric membrane method. If a designer of the WTP is considering ceramic membrane with 2.0 m/d flux, the price of ceramic membrane module should be less than 510 USD/m^2 or 4.25 times of polymeric membrane's price. Those values and methodology shown in this study could be used for the relative comparison between ceramic and polymeric membranes. The prices of ceramic membranes are expected to decrease owing to the recent development of manufacturing technologies and increase of demand in many industries. Therefore, we may expect that the ceramic membranes would be widely used in many public WTPs, and that this study could be used to help the designers at the initial planning stage to analyze economic feasibility of ceramic membranes for WTP.

Acknowledgments

This research was supported by the project titled "A design guideline for water treatment system using ceramic membrane" funded by GS Engineering & Construction Corporation and Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology (Grant No. 2011-0014006).

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