Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Effect of membrane performance including fouling on cost optimization in brackish water desalination process

W.L. Ang[a,b], D. Nordin[a,b], A.W. Mohammad[a,b,*], A. Benamor[c], N. Hilal[d]

[a] Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan 43600, Malaysia
[b] Centre for Sustainable Process Technology (CESPRO), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan 43600, Malaysia
[c] Gas Processing Center, Qatar University, Doha, Qatar
[d] Centre for Water Advanced Technologies and Environmental Research (CWATER), College of Engineering, Swansea University, Swansea SA2 8PP, UK

ARTICLE INFO

Article history:
Received 27 May 2016
Received in revised form 30 September 2016
Accepted 21 October 2016
Available online 29 October 2016

Keywords:
Membrane process
Brackish water desalination
Cost model
Economic evaluation
Membrane fouling

ABSTRACT

Membrane selection is a crucial step that will affect the economic feasibility of the membrane water treatment process. A comprehensive evaluation consisting of Verberne Cost Model, assessment of membrane performance and fouling propensity, osmotic pressure differential (OPD) and specific energy consumption (SEC) was employed to determine the potential of nanofiltration (NF 270, NF 90 and TS 80) and low pressure reverse osmosis (XLE) membranes to be used in brackish water desalination process. The aim was to save costs by replacing the typical brackish water reverse osmosis (BW 30) membrane. Verberne Cost Model showed that higher flux NF membranes resulted in lower overall costs. However, after assessing the membrane performance, NF 270 and TS 80 were excluded due to their high fouling propensity and their failure to reduce total dissolved solids (TDS) in the solution. Instead, NF 90 membrane which produced water with acceptable TDS and has moderate permeability ended up to be more cost competitive compared to BW 30 membrane, with 17–21% lower total costs and 13–17% lower water costs. Apart from this, OPD and SEC were applied to justify the selection of optimal membrane recovery rate based on the water costs calculated. It was determined that the optimal recovery rate was 80% where the SEC and water costs were close to available water treatment plants. Overall, this study showed that the selection of membrane can be carried out by using Verberne Cost Model assisted by assessment of membrane performance and fouling propensity, OPD and SEC.

1. Introduction

Membrane desalination is an energy intensive process where most of the energy is being consumed to supply the necessary operating pressure. It has been reported that high pressure pumps are responsible for more than 40% of the total expenditures of membrane desalination plant (Subramani et al., 2011). In terms of power consumption, pumps consumed as much as 80% of the overall electricity supplied to desalination plant (Subramani et al., 2011). However, technological advancement in desalination process such as energy recovery devices, efficient design and operation of desalination plant managed to cut down the energy consumption from 30 kWh/m^3 in 1979 to around

* *Corresponding author at*: Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Selangor Darul Ehsan 43600, Malaysia. Fax: +60 3 89216148.
E-mail addresses: drawm@ukm.edu.my, awm.ukm@gmail.com (A.W. Mohammad).
http://dx.doi.org/10.1016/j.cherd.2016.10.041

Nomenclature

$C_{chemical}$	Chemicals costs (€)
C_{civil}	Civil investments (€)
$C_{consump}$	Consumption costs (€)
C_{deprec}	Depreciation costs (€)
$C_{electro}$	Electrotechnical investments (€)
C_{energy}	Energy costs (€)
C_{invest}	Total investments costs (€)
C_{maint}	Maintenance costs (€)
C_{mech}	Mechanical investments (€)
$C_{membrane}$	Membrane investments (€)
$C_{operating}$	Total operating costs (€)
C_{spec}	Specific operation costs (€)
n	Number of membrane modules
P	Operating pressure (bar)
Q_F	Feed flow (m^3/h)
Q_P	Permeate flow (m^3/h)

3.9 kWh/m^3 today. Furthermore, with the most recent developments, it has been demonstrated that the energy consumption by seawater reverse osmosis (SWRO) desalination process can be reduced to roughly 2.0 kWh/m^3 (Chang et al., 2008). Although the energy consumption of SWRO desalination has been substantially reduced, it is still considerably higher than conventional surface water treatment technologies. Since reducing the energy consumption is critical for lowering the desalination water costs, consideration should be given in using brackish water with lower osmotic pressure or in selecting membrane with higher rejection but at lower operating pressure (Chang et al., 2008; Cobry et al., 2011).

Brackish water contains much lesser dissolved mineral salts which indicate the operating pressure for the membrane process can be lowered down significantly, as compared to seawater desalination process. This opens the opportunity for nanofiltration (NF) membrane to be used in brackish water treatment process, since NF membrane offers higher water production (permeate) while operating at lower pressure compared to reverse osmosis (RO) membrane. Higher production rate also reflects the chance to reduce energy consumption and increase the economic values of the desalination plant. Theoretically, the application of NF membrane in brackish water desalination process would be favorable due to its advantages over RO membrane as aforementioned (Ang et al., 2014). However, this comes at the expense of lower membrane salt rejection capability as high permeability membrane normally has high salt permeability too (Shrivastava et al., 2015). In other words, further treatment is required to get the permeate TDS concentration down to the recommended range. This might incur extra costs for the additional treatment process and offset the benefit of high flux performance. The cost comparison study among different types of NF and RO membranes for brackish water desalination has been limited and this information is required to know to what extent the NF membrane is economically preferable than RO membrane. Such comparison is also important to clarify the arguments about the use of high permeability membrane will not result in significant energy and cost savings (Shrivastava et al., 2015).

Economic evaluation can provide the necessary cost comparison among different membranes and also the required information before decision of new investment on the membrane treatment plant can be made (Van der Bruggen et al., 2001; Suárez et al., 2015). The cost of membrane water treatment plant varies and is dependent on the production capacity, type of treatment involved, design criteria, climate condition, characteristics of land and building, etc. Membrane flux or the production capacity is the most important aspect for the design of membrane filtration plant as it is a direct measure of productivity, operating pressure (energy requirements) and amount of membrane required (membrane area) (Wiesner et al., 1994; Verberne and Wouters, 1993; Sethi and Wiesner, 2000). Hence, a cost model which utilizes simple experimental results such as flux and rejection yet capable to provide acceptable cost estimation is desirable for the selection of appropriate membrane of a new water treatment plant.

Various cost models have been developed to provide estimation of total costs for planning, initial screening purposes and to better understand the impacts of different designs and operating conditions on membrane treatment costs (Van der Bruggen et al., 2001; Sethi and Wiesner, 2000; Bick et al., 2012; Guerra and Pellegrino, 2012; Macedonio et al., 2007; Mohammad et al., 2007). Among the available models, Verberne Cost Model will be of particular interest since the equations involved were based on project practical data and it has been successfully employed in estimating the cost of membrane water treatment process based on simple experimental results (Van der Bruggen et al., 2001; Mohammad et al., 2007). However, Verberne Cost Model does not take membrane fouling propensity into consideration. It is widely known that fouling plays a vital role in affecting the overall membrane performance and this will have significant impact on the capital and operating costs. Furthermore, as mentioned above, energy consumption and desalinated water costs are particularly important where both are heavily dependent on membrane recovery rate and difficult to be justified by Verberne Cost Model. Considering Verberne Cost Model alone is not enough to provide a comprehensive evaluation of membrane treatment process, the membrane performance, fouling propensity and energy consumption also have to be included during the selection of membrane for the water treatment plant.

This study attempted to utilize Verberne Cost Model in predicting the total costs of membrane brackish water desalination processes using different NF and RO membranes. Economic evaluation from the cost model will be combined with membrane fouling propensity and performance for the selection of appropriate membrane to replace the typical brackish water RO membrane with the aim to save costs. In addition, energy consumption, represented by osmotic pressure differential (OPD) and specific energy consumption (SEC) was adopted to assist in the determination of optimal membrane recovery rate based on the water cost calculated from Verberne Cost Model. Overall, a comprehensive evaluation including Verberne Cost Model supported by membrane performance, fouling propensity and energy consumption will be carried out to assess and decide which membrane performs the best and suitable for this brackish water desalination process. The rationales behind the use of high permeability membrane and its impact on energy and cost savings will also be evaluated.

2. Materials and methods

2.1. *Chemicals and membranes*

All chemicals used are analytical grade, unless stated otherwise. Humic acid (HA), ferric chloride ($FeCl_3$), kaolin, calcium chloride ($CaCl_2{\cdot}2H_2O$), sodium bicarbonate ($NaHCO_3$), and sodium chloride (NaCl) were purchased from Sigma–Aldrich (Malaysia). Ultrapure (UP) water with a quality of 18 MΩ cm^{-1} was used for all solution preparation. Membrane used in this study can be divided into two categories; NF membranes (NF 270, NF 90 and TS 80) and RO membranes (XLE and BW 30). All of the membranes were purchased from Dow Filmtec (USA) except for TS 80 membrane which was purchased from Trisep (USA). The characteristics of the membranes are shown in Table 1. BW 30 membrane will be the control membrane in this study where its performance will be the benchmark for other membranes. NF 270 membrane is known to be a high flux NF membrane while NF 90 has high salt rejection capability with moderate flux. TS 80 is a NF membrane that has slightly higher flux over BW 30. XLE is a RO membrane which was specifically fabricated to be operated with lower energy consumption (lower operating pressure and higher flux compared to typical RO membrane).