

Energy saving methodology for the SWRO desalination process: control of operating temperature and pressure

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Abstract

This study proposes a new operation methodology for energy saving in the Fujairah seawater reverse osmosis (SWRO) plant, as the optimum feed pressure is determined at the controlled operating temperature. To this end, two functional models were developed by genetic programming (GP) using two-year operational data. The data revealed that the required feed pressure for the plant operation was potentially overestimated. Based on the developed models, simulation of a three-step sequential control was carried out to reduce and optimize the required feed pressure. The simulation results first indicate that the temperature control significantly reduces the required feed pressure at a reasonably high temperature. Second, as the permeate water flow rate (PFR) is determined by the optimized feed pressure instead of the permeate pressure actually used to maintain a steady PFR in Fujairah, the required feed pressure could be substantially reduced. As a result, the proposed methodology can potentially reduce the required feed pressure, by approximately 10 bar, under

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the identical performance of both PFR and permeate water total dissolved solids (TDS). This study implies that the optimization of operation and management of MSF-hybridized SWRO processes can considerably improve the efficiency of the desalination process in terms of energy and, eventually, cost saving.

Keywords: Seawater reverse osmosis (SWRO); Desalination; Optimization; Required feed pressure; Temperature correction factor (TCF); Genetic programming (GP)

1. Introduction

Due to increases in population and environmental pollution, water shortage is becoming an evermore serious global problem. In addition, the costs incurred by conventional drinking water production have also been increasing due to the deterioration of freshwater resources (i.e., rivers, lakes, and groundwater). Accordingly, humans have started to focus more on seawater, with more than 97% of the total amount of water on Earth, as a means of supporting insufficient freshwater resources. Current desalination processes for converting seawater to freshwater, i.e., seawater reverse osmosis (SWRO) and multistage flash (MSF), have been used as alternative means of securing water resources. Especially, since the cost of water production using SWRO desalination processes is gradually decreasing due to advances in desalination technology [1], compared to MSF processes, SWRO has become a popular solution for increasing the water supply.

To improve the SWRO process efficiency, a number of studies have been conducted to investigate factors affecting process performance, such as operating pressure, operating temperature, concentration polarization, degree of fouling and scaling, water quality, and specific membrane characteristics [2–6]. In particular, it is believed that the operating pressure and temperature can be used as controllable factors to improve process performance as the net driving pressure (NDP), which is strongly influenced by the operating pressure, is capable of controlling the permeate water flow rate (PFR) [6]. Also, the operating pressure can

affect the total dissolved solids (TDS) in the permeate; in a previous study [7], it was shown that the operating pressure could be reduced by controlling the expected permeate TDS. However, the study did not consider the temperature effect on the SWRO process, as an increase in the operating temperature causes corresponding PFR and permeate water TDS increases due to a decrease in water viscosity [7,8]. This result implies that there is potential to further reduce the operating pressure at a reasonably high temperature under identical PFRs.

Therefore, this study focuses on controlling both the operating temperature and pressure as a means of optimizing the Fujairah SWRO process, and saving energy. To simulate the process performances (i.e., the PFR and permeate TDS) according to the operating conditions, two functional models based on two-year operational data sets were generated using genetic programming (GP). To determine the optimized feed pressure, simulations of three-step sequential controls were carried out by adding the PFR control and then removing the permeate pressure control as the main control of the operating temperature, using the generated models.

2. Materials and methods

2.1. Data description

The Fujairah desalination plant in the United Arab Emirates (UAE) is currently one of the largest desalination plants in the world and can produce 100 MIGD (454,000 m³/day) of freshwater as a hybrid system consisting of MSF (62.5% of total freshwater production)

and SWRO (37.5%) systems. The plant was constructed in 2003 and operated at a reduced capacity (approximately 30% of full capacity) during its first two years (2003–2004) due to a lack of demand for treated water [9]; it has been operating at full capacity since 2005. Accordingly, to develop prediction models that consider the full operational capacity of the plant, operational data from January 2005 to February 2007 was selected for this study. The observed data consist of five input variables (i.e., feed seawater temperature, feed TDS, feed pressure, permeate pressure, and feed water flow rate) and two output variables (i.e., PFR and permeate TDS).

2.2. Principle

Based on the solution diffusion model, the equations for calculating the PFR (Q_w [m³/h]) and permeate salt flow rate (Q_s [g/h]) can be derived as follows [10,11]:

$$Q_w = A \cdot S \cdot (\Delta P - \Delta \pi) = A \cdot S \cdot \text{NDP} \quad (1)$$

$$Q_s = B \cdot S \cdot (C_f - C_p), \quad C_p = \frac{Q_s}{Q_w + Q_s} \approx \frac{Q_s}{Q_w} \quad (2)$$

where A [m/h-bar] and B [m/h] are the empirically obtained water and salt transport coefficients, respectively, S [m²] is the RO membrane surface area, ΔP [bar] is the transmembrane pressure, $\Delta \pi$ [bar] is the differential osmotic pressure between the feed and permeate sides of the RO spiral wound membrane, NDP [bar] is the net driving pressure, C_f [ppm] is the feed water concentration in TDS, and C_p [ppm] is the permeate water concentration in TDS.

The transmembrane pressure (ΔP), osmotic pressure (π), and NDP can be calculated using the following formulas [11]:

$$\Delta P = P_f - P_p - \frac{\Delta P_{\text{drop}}}{2} \quad (3)$$

$$\pi = 0.082 \times 10^{-3} \cdot (273.15 + T) \cdot \sum m_i \quad (4)$$

$$\text{NDP} = (P_f - P_p - \frac{\Delta P_{\text{drop}}}{2}) - (\pi_f - \pi_p) \quad (5)$$

where P [bar] and T °C represent the pressure and operating temperature, respectively. In addition, ΔP_{drop} is the pressure drop and m_i is the molality of water [mols of solute per kg of solvent]; subscripts f and p indicate the feed side and permeate side of the membrane, respectively.

The salt passage (SP) ratio [%] as an index of the performance of the SWRO membrane process and the permeate salt flow rate are defined as [10]:

$$\text{SP}(\%) = 100 \times \frac{C_p}{C_{f,\text{ave}}}, \quad C_{f,\text{ave}} = C_f \ln \left[\frac{1}{R(1-R)} \right] \quad (6)$$

where $C_{f,\text{ave}}$ [ppm] is the average TDS concentration of the feed side and R is the water recovery ratio from seawater to freshwater.

To further investigate the effects of temperature on the SWRO desalination process, a temperature correction factor (TCF) can be used. It is known that the influence of temperature on membranes varies according to the type of membrane (i.e., spiral wound and hollow fiber), membrane material (i.e., cellulose acetate and polyamide composite), and membrane manufacturer. Therefore, the parameter U in Eq. (7) can be used as a correction factor for the effects of temperature, empirically obtained from the conditions mentioned above [12]:

$$\text{TCF} = \exp \left[U \times \left(\frac{1}{298} - \frac{1}{273+T} \right) \right] \quad (7)$$

Using a standardization method based on the standard condition obtained by experimental operation, the normalized PFR

$(Q_{w,a}/Q_{w,s})$ that considers TCF can be estimated using Equation [12]:

$$\frac{Q_{w,a}}{Q_{w,s}} = \frac{TCF_a}{TCF_s} \times \frac{NDP_a}{NDP_s} \tag{8}$$

here, subscripts *a* and *s* represent the actual and standard values, respectively.

And the normalized salt passage ratio (SP_a/SP_s) that considers the NDP can be calculated as [12]:

$$\frac{SP_a}{SP_s} = \frac{NDP_a}{NDP_s} \times \frac{C_{p,a}/C_{p,s}}{C_{f,a}/C_{f,s}} \tag{9}$$

In order to develop a prediction model for PFR and the permeate water TDS using GP, two functional forms [Eqs. (10) and (11)] affecting TCF can be defined by the previous equations with the following parameters:

$$\overline{Q_w} = f(TCF, \overline{A}, \overline{NDP}) \tag{10}$$

$$\overline{SP} = f(TCF, \overline{B}, \overline{NDP}, \overline{C_f}) \tag{11}$$

where the upper bars indicate the normalized Q_w and SP generated by GP (see the next section).

Since GP is an evolutionary algorithm based on a heuristic method and determines the functional model by considering the numerical effect of each parameter value based on repeated learning from the given accumulated data sets, it is difficult to assign some physical meanings in these equations. Thus, it should be noted that the functional forms can change depending on the learning data sets and that these equations are deemed applicable to this case study only.

2.3. Normalization

To apply actual operating data to GP, it is first necessary to normalize each parameter (i.e., Q_w , TCF, *A*, NDP, *SP*, *B*, and C_f). Here,

Table 1

Operating parameter values at the reference condition of 25°C

Parameter	Value
Temperature (°C)	25.00
Feed TDS (ppm)	36,200
Feed pressure (bar)	67.10
Permeate pressure (bar)	11.30
Pressure drop (bar)	2.01
Water transport coefficient (m/hr-bar)	1.13 E-03
Permeate water flow rate (m ³ /h)	456
Salt transport coefficient (m/s)	1.10 E-04
Permeate water TDS (ppm)	369
Recovery ratio (%)	42.80

the operating data at 25°C was employed as a reference condition [i.e., same meaning as in the standard condition described in Eqs. (8) and (9)], shown in Table 1, as TCF becomes 1.0 at 25°C [see Eq. (7)]. In this case, the normalized data can be determined as a ratio of actual values (subscript *a*) and reference values (subscript *r*) in each parameter [7]:

$$\begin{aligned} \overline{Q_w} &= \frac{Q_{w,a}}{Q_{w,r}}, \overline{A} = \frac{A_a}{A_r}, \overline{NDP} = \frac{NDP_a}{NDP_r}, \\ \overline{SP} &= \frac{SP_a}{SP_r}, \overline{B} = \frac{B_a}{B_r}, \overline{C_f} = \frac{C_{f,a}}{C_{f,r}} \end{aligned} \tag{12}$$

2.4. Development of GP models

To predict PFR and the permeate TDS, two models were developed in this study for PFR [see Eq. (10)] and salt passage ratio [see Eq. (11)] using GP; GP can automatically develop optimized functional models from a given data set consisting of input and output parameters. The GP process includes the following steps: representation of nodes and leaves, feedback fitness, and genetic operation by selection, crossover, and mutation operators. After these three steps, the optimized models can be generated; further details

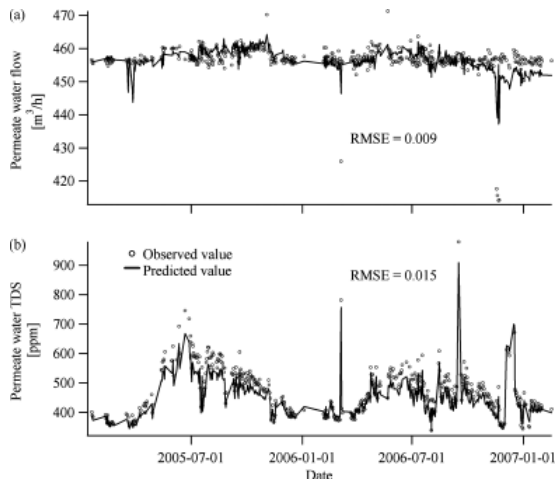


Fig. 1. Model verification based on a comparison of the observed values of the Fujairah SWRO plant with the predicted values developed by GP models: (a) permeate water flow rate and (b) permeate water TDS.

of the GP process can be found elsewhere [7,13,14].

In this study, to generate the models, the GP learning conditions were set as follows: (1) the population size was $N^{1.5}$, where N is the number of training data samples; (2) a pair-wise tournament was used as the selection strategy; (3) the probability of crossover and mutation were set at 0.75 and 0.5, respectively; and (4) each experiment was iterated until 500 generations.

As shown in Fig. 1, the values predicted for both PFR and permeate water TDS using the generated models achieved very good performance, based on a comparison with the observed data from the Fujairah SWRO plant. In the figure, the root mean square error (RMSE) values were 0.009 and 0.015, respectively, indicating good agreement between the observed and the modeled data.

3. Results and discussion

3.1. Analysis of Fujairah SWRO plant operation data

For this study, the two-year operational data from the Fujairah SWRO plant were used to

develop the prediction models. Figure 2 shows the actual operational data, which includes feed temperature, feed TDS, permeate TDS, PFR, feed pressure, and permeate pressure from January 2005 to February 2007.

In Fig. 2(a), the operating feed water temperature displays an obvious seasonal variation; the permeate water TDS was directly affected by the feed water TDS as well as the operating temperature depicted in Fig. 2(a). Comparing the trends of these two parameters with the permeate water TDS, we determined that there is a possibility of reducing the permeate water TDS to under the maximum allowable TDS criteria for drinking water (less than 500 ppm), by controlling the two parameters. Also, it is well known that an MSF-hybridized SWRO system can adjust the permeate water TDS by mixing feed seawater with the high temperature water produced during the MSF process [9].

Interestingly, Fig. 2(c) shows that the Fujairah SWRO plant attempted to maintain a steady PFR. For this aim, the permeate pressure was mechanically controlled because the fixed feed pressure was overestimated during plant operation, as shown in Fig. 2(d). The downward trend in the figure (see the dotted line) implies that the permeate pressure should be controlled as it tends to decrease with time because of the deterioration of membrane performance by fouling and scaling. This trend can be further explained by Eq. (5), which shows that the overestimated feed pressure will obviously cause an increase of NDP, eventually leading to an increase of PFR.

Therefore, the manipulation of the permeate pressure shown in Fig. 2(d) is inevitable during the maintenance of the steady PFR shown in Fig. 2(c). The permeate pressure appears to be eventually controlled to satisfy the required NDP for a steady PFR, which is susceptible to fluctuation with respect to time due to the time-variant feed water temperature and deterioration of the membrane. This result reveals that the overestimation

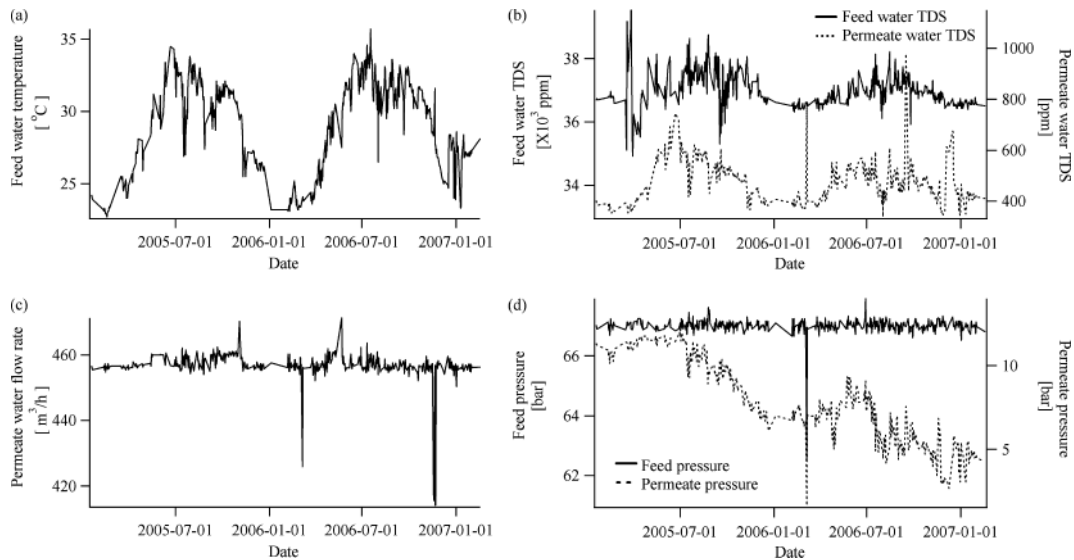


Fig. 2. Operational data from the Fujairah SWRO plant: (a) feed water temperature, (b) feed water TDS and permeate water TDS, (c) permeate water flow rate, and (d) operating feed pressure and permeate pressure.

of the required feed pressure may incur an increase in operation and maintenance (O&M) costs.

Based on these findings, we then performed two major simulations using the developed models in an attempt to reduce the feed pressure and save energy. The first simulation increased the operating temperature to reduce the required feed pressure under identical PFR performance, because the higher operating temperature can be applied using thermal energy extracted from MSF. The other simulation attempted to remove the permeate pressure control, thereby reducing the required feed pressure while maintaining the same required NDP.

3.2. Simulations using three-step sequential control of feed temperature and pressure

For the two objectives mentioned above, a three-step sequential control with the generated GP models was performed to optimize the entire process, including the main control of operating temperature, PFR control, and

removing the permeate pressure control. The controls were sequentially carried out as follows, denoted as A, B, and C, respectively, in Fig. 3:

- A: main control of the operating temperature;
- B: temperature control (A) and PFR control;
- C: temperature and PFR controls (B) by removing the permeate pressure control.

To compare the effects of temperature on process performance, three optimal temperature conditions (27.5, 31.5, and 35°C) were applied to the Fujairah SWRO plant (see A-1 in Fig. 3), based on previous research [7,15]. The first simulation was carried out at 27.5°C (see the gray line in the figure), the optimized point for both the expected PFR and permeate water TDS in the Fujairah SWRO plant [15]. The second was at 31.5°C (see the dotted line), which was under the maximum allowable permeate water TDS criteria for drinking water. And the last one was at 35°C (see the black line), the upper operating temperature limit of the membranes, to protect them from degrading due to high temperature. In

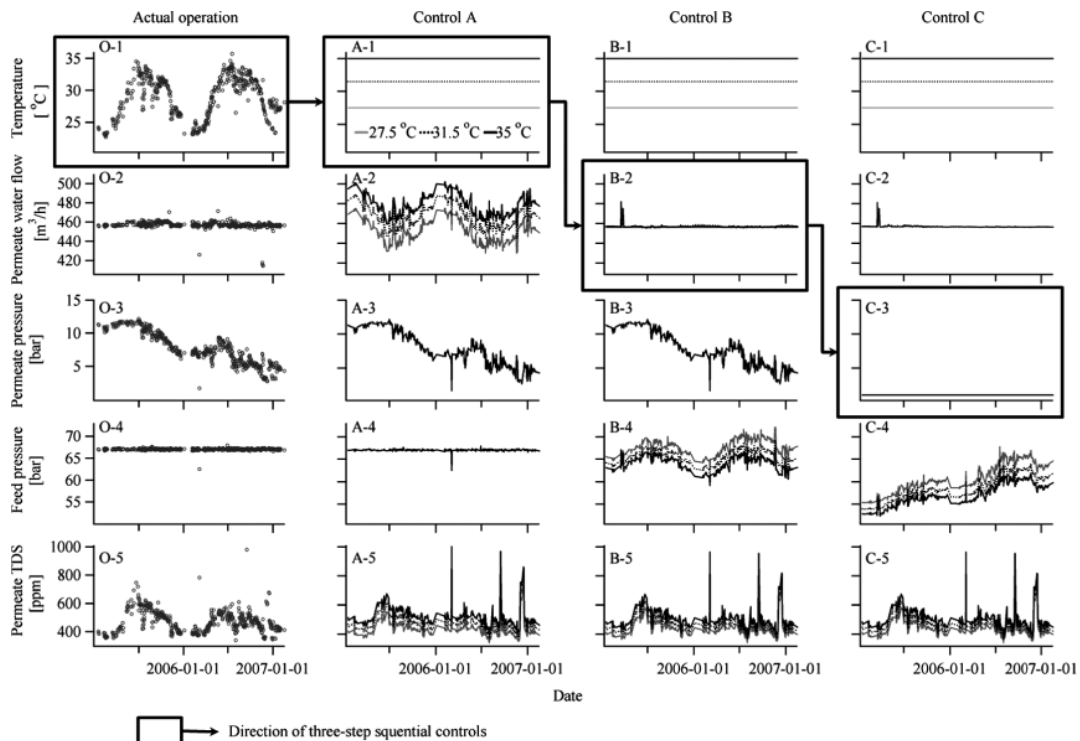


Fig. 3. Results and conditions of three-step sequential simulations for operating temperature (first row), permeate flow rate (second row), permeate pressure (third row), required feed pressure (fourth row), and permeate water TDS (fifth row). Columns represent the actual operational data at the Fujairah SWRO plant (column O); control A: main control of the operating temperature (column A); control B: temperature control and PFR control (column B); and control C: temperature and PFR controls by removing the permeate pressure control (column C).

control A, PFR and the permeate water TDS were found to significantly increase at higher controlled temperature than at the observed operating temperature (see A-2 and A-5).

In control B, the PFR was additionally controlled using the model generated by GP [see Eq. (10)] to the average value (456 m³/h) of the original operation (compare O-2 and B-2), thus indicating that the feed pressure can be reduced as the operating temperature increases (see B-4).

Finally, in the control C, atmospheric pressure (1.01 bar) was applied to the permeate pressure (see C-3) to attempt to remove the permeate pressure control. The result shows that the feed pressure can be lowered (comparing see C-4 to O-4), while maintaining

identical performance in terms of both PFR and permeate water TDS (compare the magnitude and trend of O-2 and O-5 with C-2 and C-5, respectively); it was also shown that the feed pressure can be reduced as the operating temperature increases. Eventually, it is expected that the algorithm for control C can be utilized in a general energy saving methodology.

3.3. Energy saving algorithm and results for the SWRO desalination process

Based on the above results, Fig. 4 presents the methodology for the optimized control of the operating temperature and feed pressure as an algorithm for the entire process. The

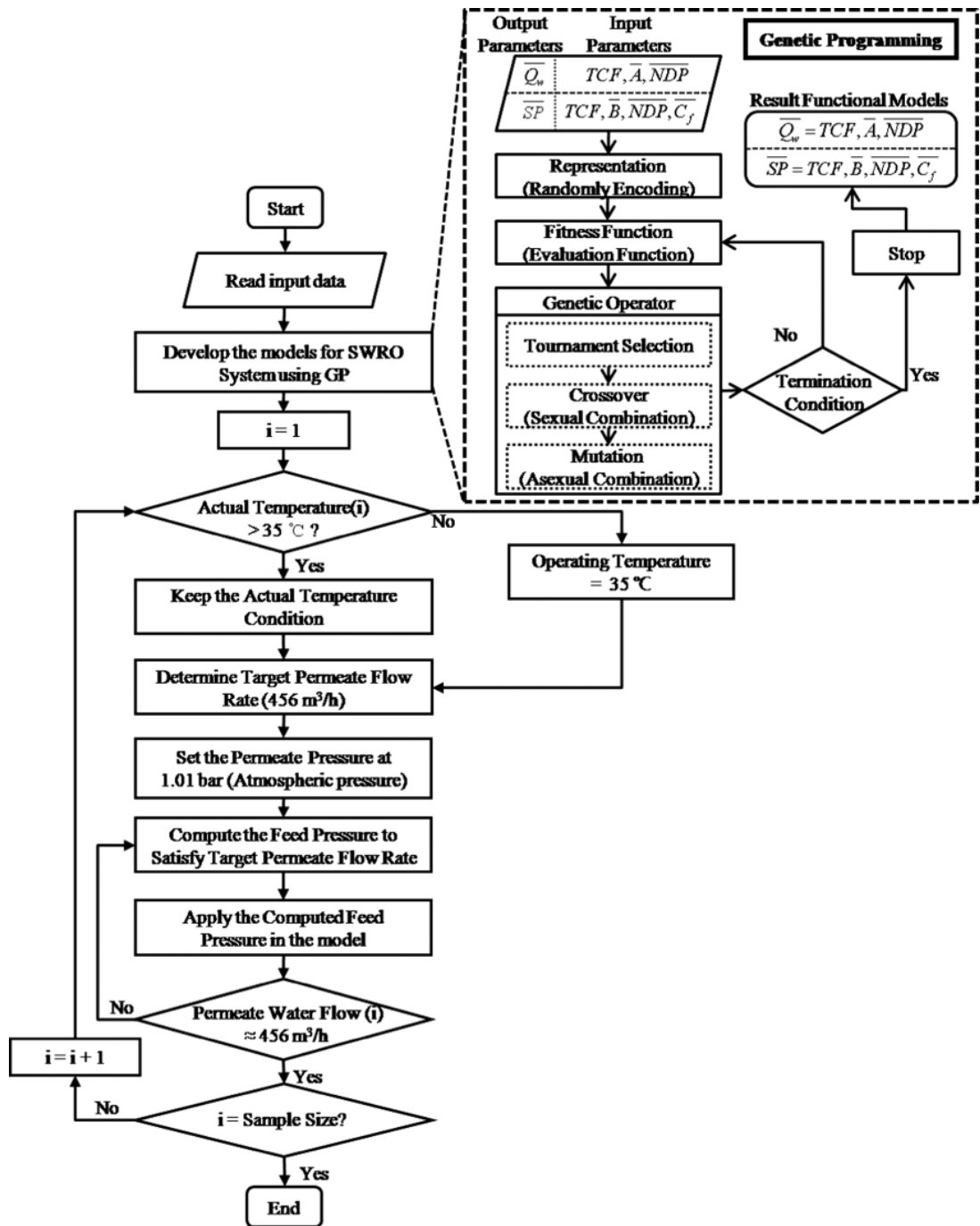


Fig. 4. Energy saving algorithm for a SWRO desalination process based on the models generated by GP.

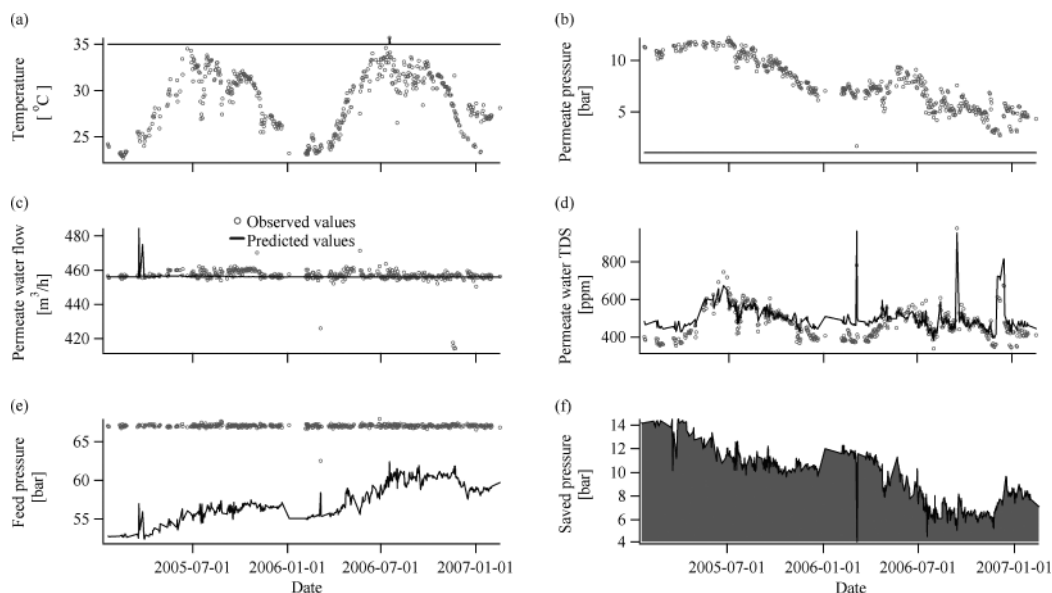


Fig. 5. Comparison of results of the proposed methodology between the observed values and the predicted values based on the GP models: (a) operating temperature, (b) permeate pressure, (c) permeate water flow rate, (d) permeate water TDS, (e) operating feed pressure, and (f) results of pressure-saving by reducing the required feed pressure.

aim of this algorithm is to optimize the feed pressure based on the models generated for the Fujairah SWRO plant. In this algorithm, the upper limited temperature was set 35°C in order to prevent from physical degradation of the polymeric membrane due to high temperature. The target PFR can then be determined based on the average performance of the original operation (456 m³/h). Next, the permeate pressure is set at the atmospheric pressure (1.01 bar). Following GP and the numerical procedures in the algorithm, the required feed pressure that satisfies the target PFR can be calculated using the models with the same degree of process performance in both PFR and permeate TDS.

Figure 5 summarizes the results when the proposed methodology is applied to the Fujairah SWRO plant. As shown in Fig. 5(a) and (b), the operating temperature and the

permeate pressure were set to 35°C and 1.01 bar for the optimized control, respectively. The results of the process performances (i.e., PFR and permeate water TDS) are seen to be very similar to the actual product of the Fujairah SWRO plant operation [see Fig. 5(c) and (d)]. Thus, the required feed pressure can be reduced using the proposed methodology [see Fig. 5(e)]; average feed pressure savings of approximately 10 bar could be achieved [see Fig. 5(f)].

4. Conclusions

Two functional models for the permeate flow rate and salt passage ratio were developed using genetic programming based on the two-year operational data of the Fujairah SWRO plant, currently the largest desalination plant in the world, a hybrid system consisting of

SWRO and MSF. The results of this study show that the hybrid desalination plant has a significant economic potential because utilization of the thermal energy extracted from the MSF process (i.e., the operating temperature control by mixing feed seawater with the high temperature water produced by the MSF process) can improve the efficiency of the SWRO process. Moreover, it was shown that applying the nonisobaric feed pressure control to the plant can reduce the required feed pressure for the entire process. Thus, the application results of the proposed methodology show substantial energy savings in terms of reducing the required feed pressure, approximately 10 bar under the identical performances of both PFR and permeate water TDS in the Fujairah SWRO process. These results further imply that optimized operation and management (O&M) plans are critically important in enhancing the efficiency of the desalination process in the sense of energy and, eventually, cost savings.

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Nomenclature

T	water temperature, °C
P	pressure, bar
C	water concentration in TDS, ppm
S	RO membrane surface area, m ²
Q_w	permeate water flow rate, m ³ /h

A	water transport coefficient, m/h-bar
ΔP	transmembrane pressure, bar
$\Delta\pi$	differential osmotic pressure between the feed and permeate sides of RO membrane, bar
ΔP_{drop}	transmembrane pressure drop, bar
Q_s	permeate salt flow rate, g/h
B	salt transport coefficient, m/h
π	osmotic pressure, bar
m_i	molality of water, mols of solute per kg of solvent
$C_{f,\text{ave}}$	average TDS concentration of the feed side, ppm
R	water recovery ratio from seawater to freshwater
U	correction factor for the effects of temperature
N	number of training data samples

Abbreviations

NDP	net driving pressure, bar
PFR	permeate water flow rate, m ³ /h
TDS	total dissolved solids, ppm
SP	salt passage ratio, %
TCF	temperature correction factor
RMSE	root mean square error

Subscripts

f	feed side of the membrane
p	permeate side of the membrane
a	actual value
s	standard value
r	reference value

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