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Design, Operation, and Control of Stand-Alone Hybrid Membrane Osmosis Desalination Systems

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Reverse osmosis (RO) is one of the major technologies for seawater desalination, while pressure retarded osmosis (PRO) is a promising technology for power generation. The RO desalination plant has the problems of extensive energy consumption and brine discharge, which can be alleviated by hybridizing the RO process with the PRO process as an integrated RO/PRO system. This study is to pursue a higher goal, that is, the power generated by the PRO unit can provide the energy consumption required for the entire hybrid system. Namely, the hybrid membrane osmosis system can achieve stand-alone operation (without external energy supply) for seawater desalination. In this study, mathematical programming models are developed for the design, operation, and control of the stand-alone hybrid membrane osmosis desalination systems. First, optimal design for two configurations of the hybrid osmosis system (i.e., RO-PRO and PRO-RO systems) is investigated. The result shows that the PRO-RO system is a more favorable design configuration for stand-alone desalination. Because the membrane system operation is bound to be affected by membrane fouling, this study explores the effects of membrane fouling on the stand-alone operation of the systems, and proposes an open-loop control scheme to determine the optimal operating strategy under membrane fouling. Finally, a closed-loop control scheme of model predictive control is proposed for the PRO-RO system to instantly compensate for the effects of unknown disturbances and modeling errors on the stand-alone operation of the desalination system.

1. Introduction

Because of rapid population growth and economic expansion, water scarcity and energy shortage are today's major issues. To exploit sustainable resources for acquiring water and energy, membrane related technologies have been developed to desalinate seawater and produce power using salinity gradient. Seawater desalination is one of the important methods for providing drinking water, and reverse osmosis (RO) process is currently the mainstream technology for seawater desalination. However, the main problems of RO desalination are considerable energy consumption and environmental impact due to brine discharge. The pressure retarded osmosis (PRO) process is an emerging green power generation technology which retrieves energy from the difference in salt concentrations between two solutions. When a low-salinity feed solution (FS) and a pressurized high-salinity draw solution (DS) are separated by a membrane, water permeates from the FS into the DS, and the gained hydraulic energy in the DS may be harvested by a hydro-turbine. The integration of RO and PRO processes can provide the RO energy demand and alleviate the problem of brine discharge.

Altaee et al. (2015) compared two configurations of RO-PRO and PRO-RO, and discussed the power generation and energy consumption of each hybrid system. Almansoori and Saif (2014) established a two-stage RO and PRO hybrid system in series to minimize the cost under different water and power requirements. Kim et al. (2013) proposed four different process flowsheets of RO and PRO in series, and analyzed the required feed conditions and area ratios in order to obtain the maximum profits of water and electricity production. In most works regarding the RO/PRO hybrid systems, the PRO power generation is used to provide part of RO energy consumption. He et al. (2014) used the thermodynamic model to analyse the RO-PRO system under the stand-alone operating condition, but practical issues such as concentration polarization and membrane fouling had not been considered.

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Membrane fouling is an inevitable phenomenon in membrane-related processes. As operation time increases, the colloidal particles attached to the membrane surface will decrease the water flux through the semi-permeable membrane, causing performance degradation of RO water production (Jeong et al., 2017) and PRO power generation (Nagy et al., 2018). Therefore, practically stand-alone operation of hybrid osmosis systems should take the membrane fouling effects into consideration.
In this paper, the design, operation, and control of the stand-alone hybrid membrane osmosis desalination systems are presented. Two configurations of the hybrid osmosis desalination systems (i.e., RO-PRO and PRO-RO) with rigorous mathematical modeling for each osmosis unit are considered. Optimal design for the hybrid systems under stand-alone operation is obtained through minimizing the specific total membrane area requirement. However, the operation of the membrane osmosis process is bound to be affected by membrane fouling. Based on fouling models, this study explores the effect of membrane fouling on system energy and water production efficiency, and proposes a dynamic adjustment strategy of operational variables (e.g., applied pressure in RO and PRO) to cope with the fouling effects. The optimal operating strategy is obtained by maximizing the water production while maintaining stand-alone operation of the system in a time period. Finally, a model predictive control (MPC) application for the PRO-RO system is proposed to compensate for the effects of unknown disturbances and modeling errors on the stand-alone operation of the system.

2. Hybrid membrane osmosis desalination system

Figure 1 shows two configurations that connect the osmosis processes in series with reverse order (i.e., RO-PRO and PRO-RO). In the RO-PRO system, pressurized seawater feeds to the RO unit and then the discharged brine feeds to the PRO unit as the draw solution. This configuration is beneficial for the PRO power generation because a higher salinity gradient becomes available. In the PRO-RO system, seawater feeds to the PRO unit as the draw solution and then the diluted draw solution feeds to the RO unit for water production. This configuration is beneficial for RO water production because the salinity of RO inlet is reduced. Impaired water (e.g., municipality water or wastewater) is used as the feed solution of the PRO unit. The pressure exchanger (PX) is an energy recovery device that transfers pressure from a high-pressure stream to a low-pressure one. Hydro-turbine (HT) generates power when the PRO draw solution partly passed it.

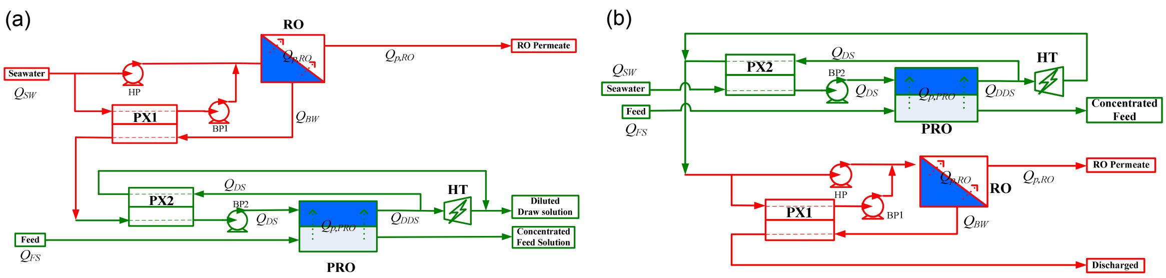

Figure 1: Schematic diagrams of the hybrid membrane osmosis system (a) RO-PRO and (b) PRO-RO

2.1 Model of RO process

The water flux J_w and the salt flux J_s equations are expressed by

$$J_w = A(\Delta P - \Delta\pi_m) \ ; \quad J_s = B\Delta c_m \tag{1}$$

where A is the water permeability coefficient, ΔP is the hydraulic pressure, $\Delta\pi_m$ is the osmotic pressure difference between both sides of the membrane, B is the salt permeability coefficient, and Δc_m is the concentration difference between both sides of the membrane. The osmotic pressure difference between both sides of the membrane can be calculated by the modified van't Hoff formula (Jeong et al., 2017):

$$\Delta\pi_m = N_{ion} R_g T \Delta c_m / M_s \tag{2}$$

where N_{ion} is the van't Hoff factor, R_g is the ideal gas constant, T is the temperature, and M_s is the molecular weight of the solution.
For seawater feed flowing through the entire membrane channel, the spatial distributions of the flow velocity (u_x), concentration (c_x) and hydraulic pressure (ΔP_x) along the axial direction are given by (Jeong et al., 2017)

$$\frac{du_x}{dx} = -\frac{J_w}{H} \ ; \quad \frac{dc_x}{dx} = \frac{c_x J_w - J_s}{H u_x} \ ; \quad \frac{d\Delta P_x}{dx} = -12K\mu \frac{u_x}{H^2} \tag{3}$$

where x represents the distance along the axial direction, H is the channel height, μ is the viscosity, and K is the friction coefficient of the channel wall.

Since most of the salt in the RO feed flowing through the semi-permeable membrane is blocked and unable to penetrate, the closer to the feed-side membrane surface, the higher the concentration. The concentration difference between both sides of the membrane surface will become larger and cause a decrease in the water flux. This phenomenon is called the concentration polarization which can be expressed by

$$\frac{c_m - c_p}{c_x - c_p} = \frac{\Delta c_m}{c_x - c_p} = \exp\left(\frac{J_w}{k}\right) \tag{4}$$

where c_m is the membrane surface concentration on the feed-side, c_p is the concentration of the permeate, and k is the mass transfer coefficient. The permeate flow rate of the RO unit with membrane area $A_{m,\mathrm{RO}}$ is given by

$$Q_{p,\mathrm{RO}} = \int_0^{A_{m,\mathrm{RO}}} J_w \, dA \tag{5}$$

2.2 Model of PRO process

In the PRO process, the water flux and the salt flux equations are expressed as follows:

$$J_w = A\left(\Delta\pi_m - \Delta P\right) \ ; \quad J_s = B\Delta c_m \tag{6}$$

The osmotic pressure difference on the draw- and feed-side membrane surfaces can be calculated by Eq(2).
In the process of the two streams of the draw solution and feed solution flowing through the entire membrane channel, the spatial distributions of the flow velocity and concentration of the two streams along the axial direction are given by (Kim et al., 2016)

$$\frac{du_{x,d}}{dx} = \frac{J_w}{H_d} \ ; \quad \frac{du_{x,f}}{dx} = -\frac{J_w}{H_f} \ ; \quad \frac{dc_{x,d}}{dx} = \frac{-J_s - c_{x,d}\, J_w}{H_d\, u_{x,d}} \ ; \quad \frac{dc_{x,f}}{dx} = \frac{J_s + c_{x,f}\, J_w}{H_f\, u_{x,f}} \tag{7}$$

where H_d and H_f are the heights of draw-side and feed-side channels, respectively.
The concentration polarization phenomenon for the PRO process can be expressed by

$$\Delta c_m = \frac{c_{x,d}\exp\left(-\frac{J_w}{k_d}\right) - c_{x,f}\exp\left(J_w\left(\frac{1}{k_f} + \frac{S_s}{D_s}\right)\right)}{1 + \frac{B}{J_w}\left(\exp\left(J_w\left(\frac{1}{k_f} + \frac{S_s}{D_s}\right)\right) - \exp\left(-\frac{J_w}{k_d}\right)\right)} \tag{8}$$

where k_d and k_f are respectively the mass transfer coefficients of the draw solution and feed solution, and S_s and D_s are respectively the structure parameter and diffusion coefficient of the support layer. The water flow rate across the membrane of the PRO unit with membrane area $A_{m,\mathrm{PRO}}$ is given by

$$Q_{p,\mathrm{PRO}} = \int_0^{A_{m,\mathrm{PRO}}} J_w \, dA \tag{9}$$

2.3 Energy consumption and generation

In the hybrid osmosis system, the energy consumption (EC), which includes the required power for pumps in RO and PRO units, is given by

$$\mathrm{EC} = W_{C,\mathrm{RO}} + W_{C,\mathrm{PRO}} = \frac{\Delta P_{\mathrm{RO}}\left(Q_{in,\mathrm{RO}} - \eta_{PX}\, Q_{BW}\right)}{\eta_{\mathrm{pump}}} + \frac{\Delta P_{\mathrm{PRO}}\, Q_{DS}\left(1 - \eta_{PX}\right)}{\eta_{\mathrm{pump}}} \tag{10}$$

where ΔP_{RO} and ΔP_{PRO} are the applied pressures of RO and PRO units, respectively, $Q_{in,\mathrm{RO}}$ is the RO feed flow rate, and η is the efficiency of equipment (η_{pump} = 0.85, η_{PX} = 0.98, and η_{HT} = 0.90 in this study). The energy generation (EG) of the system comes from the hydro-turbine of the PRO unit:

$$\mathrm{EG} = W_{G,\mathrm{PRO}} = \Delta P_{\mathrm{PRO}}\, Q_{p,\mathrm{PRO}}\, \eta_{\mathrm{HT}} \tag{11}$$

When the energy generated is sufficient to supply energy consumption of the system (i.e., $\mathrm{EC} = \mathrm{EG}$), the hybrid osmosis system can operate under stand-alone condition without requiring external energy input.

3. Optimal design of stand-alone desalination system

In the design of a stand-alone desalination system, the energy cost does not need to be considered. Therefore, the operating cost of the system mainly lies on the costs of seawater pretreatment and membrane. In the case of a fixed amount of inlet seawater (Q_{SW}), the optimal design of stand-alone hybrid membrane osmosis desalination system is formulated as the following optimization problem that minimizes the specific total membrane area (STMA):

$$\min_{\mathbf{z}} \mathrm{STMA} = \frac{A_{m,\mathrm{RO}} + A_{m,\mathrm{PRO}}}{Q_{p,\mathrm{RO}}} \tag{12}$$

subject to the constraints of stand-alone operation ($\mathrm{EC} = \mathrm{EG}$) and permeate concentration limit (c_p < 500 ppm). The design variables considered are the applied pressures and membrane areas of both osmosis processes, i.e., $\mathbf{z} = \{\Delta P_{\mathrm{RO}}, \Delta P_{\mathrm{RRO}}, A_{m,\mathrm{RO}}, A_{m,\mathrm{RRO}}\}$. The flow rate of feed solution (Q_{FS}) for PRO unit is represented as a dimensionless feed flow rate defined as $\phi = Q_{FS} / (Q_{SW} + Q_{FS})$. A larger value of ϕ enhances the power generation efficiency of PRO. Here, ϕ is treated as a parameter because the value of ϕ depends on the availability of impaired water. The membrane types used in this study are SW30HRLE for RO and PRO-TFC for PRO, and their parameters are reported in Jeong et al. (2017) and Almansoori and Saif (2014). The inlet concentration of seawater and feed solution are 0.035 and 0.001 kg/L, respectively.

Figure 2 shows the optimization results under different seawater flow rates and ϕ values. The variations of optimal STMA due to feed condition changes for RO-PRO and PRO-RO systems exhibit similar trends. When ϕ or Q_{SW} becomes larger, the corresponding STMA value decreases. Under the same feed condition, the PRO-RO system has a smaller STMA compared to RO-PRO system. The effect of seawater salinity on the design result is investigated as shown in Figure 3, where not only STMA but also the water recovery ($Y = Q_{p,\mathrm{PRO}} / Q_{SW}$) is shown. The results indicate that higher seawater salinity is beneficial for stand-alone operation of hybrid systems as the systems have lower STMA and higher water recovery. The results also reveal that PRO-RO system exhibits better performance in terms of STMA and water recovery than RO-PRO system.

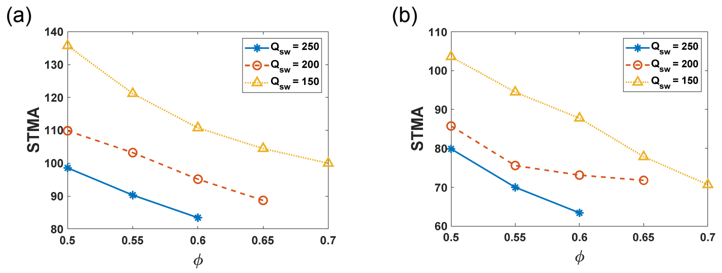

Figure 2: The optimal STMA for stand-alone desalination systems (a) RO-PRO (b) PRO-RO

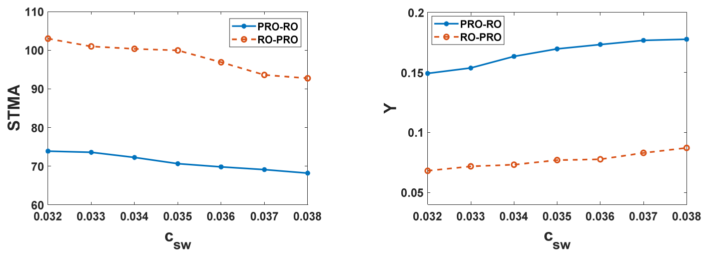

Figure 3: The effect of seawater salinity on STMA and water recovery of stand-alone desalination systems

4. Operation strategy under membrane fouling

Membrane fouling is inevitable during the operation of membrane processes. Although the hybrid system is originally designed to meet the stand-alone condition, the system with fixed operating conditions cannot maintain stand-alone operation because the energy consumption and generation will be affected by membrane fouling when the system operates. The models for membrane fouling presented in Jeong et al. (2017) and Nagy et al. (2018) are adopted in this study. Figure 4 shows the operation of hybrid systems over time (Q_{SW} = 200 m^3/d) when membrane fouling is considered. The water production ($Q_{p,\mathrm{RO}}$) for both systems decreases over time. The net energy consumption ($\Delta E = \mathrm{EC} - \mathrm{EG}$) is positive and increases over time for RO-PRO system, which means that the water production must be further reduced to maintain stand-alone operation. On the other hand, the net energy consumption is negative and decreases over time for PRO-RO system, which means that the system has a surplus of energy that can be used to produce more water.

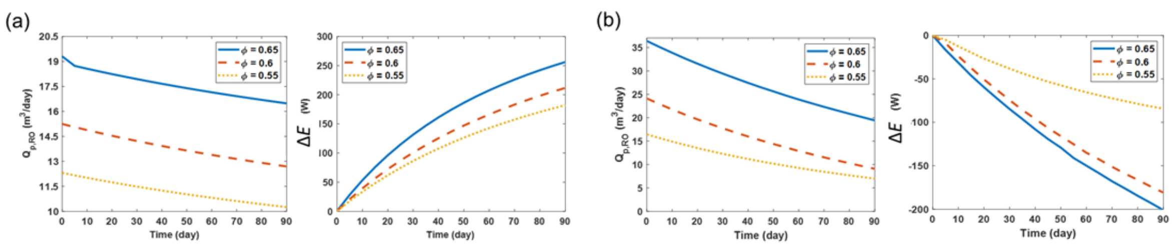

Figure 4: The effect of membrane fouling on the stand-alone desalination systems (a) RO-PRO (b) PRO-RO

With the membrane fouling consideration, the hybrid osmosis system exhibits time-varying characteristics; therefore, timely adjustment of the operating condition (ΔP_{RO} and ΔP_{PRO}) is required to maintain the stand-alone operation of the system. We consider a time period (T) between membrane cleaning, and several times instants t_i within T ($0 = t_0 < t_1 < \cdots < t_K = T$) at which instants the two applied pressures are adjusted. The determination of optimal operation strategy for stand-alone desalination system is formulated as the following optimization problem that maximizes the total water production V_p:

$$\max_{\substack{\Delta P_{\mathrm{RO}}(k),\ \Delta P_{\mathrm{PRO}}(k)\\ k=0,1,\cdots K-1}} V_p = \int_0^T Q_{p,\mathrm{RO}}(t)\,dt \tag{13}$$

subject to the following constraint of stand-alone condition in each small time interval $[t_k, t_{k+1}]$:

$$\int_{t_k}^{t_{k+1}} \mathrm{EC}(t)\,dt = \int_{t_k}^{t_{k+1}} \mathrm{EG}(t)\,dt, \quad k = 0,1,\cdots,K-1 \tag{14}$$

It is found that RO-PRO system becomes infeasible for long-term stand-alone operation under membrane fouling. Figure 5 shows the optimal operation strategy for PRO-RO system (Q_{SW} = 200 m^3/d and ϕ = 0.65). A 90-day period is considered and the applied pressures are adjusted every 15 days. Compared to the case of fixed operating conditions (without operation strategy), an increase of 23% in the total water production is achieved by the dynamic adjustment of two applied pressures. The average water recovery is 0.14.

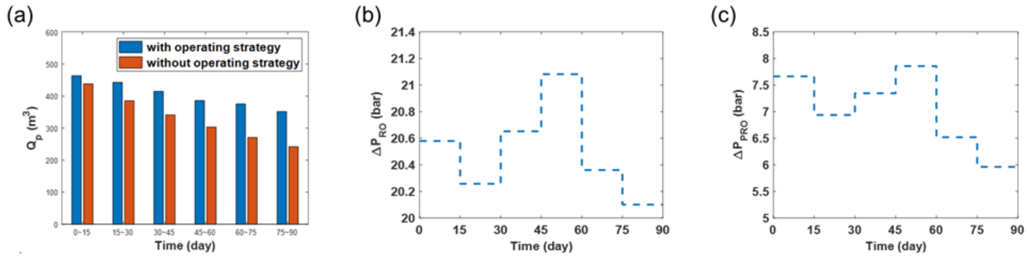

Figure 5: Results of optimal operation strategy for PRO-RO system under membrane fouling (a) water production (b) applied pressure of RO (c) applied pressure of PRO

5. Closed-loop control scheme for stand-alone operation

The determination of optimal operating strategy presented in the previous section is based on a membrane fouling model. It is an open-loop control scheme because the actual measurements of the system are not used to determine the applied pressures. As a result, the actual operation of the hybrid system may deviate from the stand-alone condition due to modeling errors and unknown disturbances. Here, a closed-loop control scheme of model predictive control (MPC) is proposed to cope with the effects of unknown disturbances and modeling errors on the stand-alone operation of the system.

Denote the applied pressures under the open-loop control scheme as $\Delta P_{\mathrm{RO}}^{\mathrm{o}}(k)$ and $\Delta P_{\mathrm{PRO}}^{\mathrm{o}}(k)$. In the closed-loop scheme, the applied pressures are modified to $\Delta P_{\mathrm{RO}}(k) = \Delta P_{\mathrm{RO}}^{\mathrm{o}}(k) + \delta P_{\mathrm{RO}}(k)$ and $\Delta P_{\mathrm{PRO}}(k) = \Delta P_{\mathrm{PRO}}^{\mathrm{o}}(k) + \delta P_{\mathrm{PRO}}(k)$, where $\delta P_{\mathrm{RO}}(k)$ and $\delta P_{\mathrm{PRO}}(k)$ are to be determined. Let the *j*-step ahead predictions of RO and PRO permeate flow rate from the process models at time instant t_k are $\hat{Q}_{p,\mathrm{RO}}(k+j)$ and $\hat{Q}_{p,\mathrm{PRO}}(k+j)$. The cumulative effects of model inaccuracy and unmeasured disturbances can lead to inaccurate predictions. With the current measurements $Q_{p,\mathrm{RO}}(k)$ and $Q_{p,\mathrm{PRO}}(k)$, the modified predictions with bias correction are given by

$$\tilde{Q}_{p,\mathrm{RO}}(k+j) = \hat{Q}_{p,\mathrm{RO}}(k+j) + \left[Q_{p,\mathrm{RO}}(k) - \hat{Q}_{p,\mathrm{RO}}(k)\right]; \quad \tilde{Q}_{p,\mathrm{PRO}}(k+j) = \hat{Q}_{p,\mathrm{PRO}}(k+j) + \left[Q_{p,\mathrm{PRO}}(k) - \hat{Q}_{p,\mathrm{PRO}}(k)\right] \tag{15}$$

These modified predictions of permeate flow rate are then used to calculate the predicted energy consumption and generation, $\widetilde{\mathrm{EC}}(k+j)$ and $\widetilde{\mathrm{EG}}(k+j)$. Define the predicted deviation to stand-alone criterion as

$$\Delta\tilde{E}(k+j) = \int_{t_{k+j}}^{t_{k+j+1}} \widetilde{\mathrm{EC}}(t)\,dt - \int_{t_{k+j}}^{t_{k+j+1}} \widetilde{\mathrm{EG}}(t)\,dt \tag{16}$$

To maintain a stand-alone operation, the control corrections for each $k = 0, 1, 2, \cdots, K-1$ are determined by

$$\min_{\substack{\delta P_{\mathrm{RO}}(k+j),\ \delta P_{\mathrm{PRO}}(k+j)\\ j=0,1,\cdots,K-k-1}} J = \sum_{j=0}^{K-k-1} \Delta\tilde{E}(k+j)^2 \tag{17}$$

This is an application of MPC with shrinking-horizon. For each k, only the first control correction is implemented. Then at the next time instant, new measurements are acquired and a new set of control corrections is calculated.

Two scenarios are presented to demonstrate the effectiveness of the proposed closed-loop control scheme. First, we consider a disturbance of seawater salinity changed from 0.035 to 0.037 kg/L at the 15th day, and the result of closed-loop control is shown in Figure 6. Because a higher seawater salinity is beneficial for stand-alone operation as mentioned previously, the system without closed-loop control has an energy surplus. By applying the MPC scheme, the system can be operated close to stand-alone condition and therefore the water production is increased. In the second scenario, we assume that the cake layer porosity in the fouling model changed from 0.5 to 0.55 at the 15th day to represent a model parameter uncertainty. The result of closed-loop control is shown in Figure 7. The system using open-loop control only will have additional net energy consumption, whereas the system with MPC scheme can operate close to the stand-alone condition.

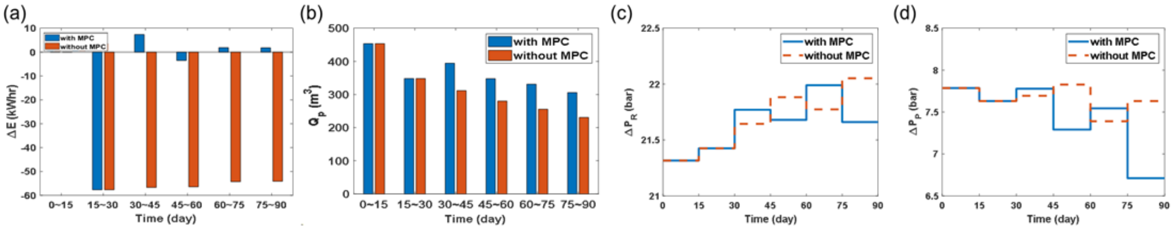

Figure 6: System operation under the disturbance using closed-loop and open-loop control schemes (a) deviation to stand-alone criterion (b) water production (c) applied pressure of RO (d) applied pressure of PRO

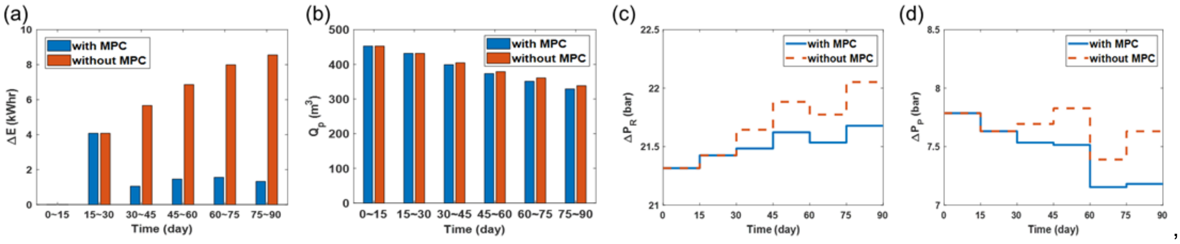

Figure 7: System operation under the modelling error using closed-loop and open-loop control schemes (a) deviation to stand-alone criterion (b) water production (c) applied pressure of RO (d) applied pressure of PRO

6. Conclusions

In this study, the optimal design, operation, and control of stand-alone hybrid membrane osmosis desalination systems are conducted based on a mathematical programming approach. It is found that the PRO-RO system is a more favorable configuration for the design of stand-alone desalination system. The proposed closed-loop control scheme (MPC approach) can effectively maintain the stand-alone operation of PRO-RO system under membrane fouling condition and in the presence of unknown disturbances and model parameter uncertainties. Although the water recovery of the stand-alone desalination system is not high, we can scale up water production using multiple membrane modules in parallel.

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