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Temporary step-wise cyclic operation controlled by DCS to mitigate fouling in RO water desalination

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ABSTRACT

This paper presents a novel technique to mitigate fouling and reduce effects of concentration polarization in reverse osmosis (RO) membranes. The technique will be referred to as the temporary step-wise cyclic operation. The method is based on superimposing a cyclic square pressure pulses on the operating pressure for a short period of time. The objective of this is to create a disturbance that may result in cleaning the membrane from reversible foulants and, hence, restoring the membrane to its normal operation. The periodic square pressure pulses were generated by superimposing oscillatory pressure pulses on the operating pressure to create instabilities. Although the use of fluid instabilities is not a new subject, the work presented here attempts to demonstrate how to program an industrial distributed control system (DCS) to perform periodic operation. The technique was implemented on a laboratory-scale RO unit that was interfaced to a Yokogawa Centum VP DCS. After the initial verification runs, the periodic operation using square wave functions of RO process was automatically performed by a DCS program, which was programmed to generate a pseudo-random binary signal course with varied frequencies superimposed on a linear control signal, thus resulting a square wave pressure signal which was onset for a short period generating eddies and turbulence that were instrumental in mitigating fouling and reduce concentration polarization. A 28.7% improvement in the permeation rate was achieved by comparing the permeate flow rate before and after imposing the mitigation technique using the superimposed square wave pressure pulse. On top of that, a reduction of conductivity from 920 to 287 µs/cm was also achieved. A comparative study on a second membrane also shows an increase of about 16% on flow rate and the conductivity came down from 1,021 to 477 µs/cm.

Keywords: Reverse osmosis; Water desalination; Fouling; DCS; Centum VP

1. Introduction

Potable water has become increasingly scarce in the last 20 years or so in many parts of the world, especially in arid and semi-arid regions. There are many solutions proposed worldwide to address the problem. One feasible solution is desalinated seawater. There are currently several technologies used to desalt water from sea water, such as multi-stage flash distillation, multi-effect distillation, vapor compression and reverse osmosis (RO). RO is popular due to its simplicity, cost effectiveness, reliability as well as lower relative energy consumption compared with the thermal processes. Unfortunately, reverse osmosis suffers a major drawback, namely, fouling of the membrane, which is exacerbated by concentration polarization. Concentration polarization also results in lower production rate as well as an increase in salt content of the product.

Fouling of RO membranes can be minimized by adequate pre-treatment steps of the feed water, but it is difficult to completely avoid it since it is likely to occur over time.

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To overcome these problems, one of the techniques that may be considered is the unsteady state operation of reverse osmosis. Unsteady operation has been proposed to reduce the concentration polarization effect and generate eddies to clean the membrane surface. One method of unsteady operation is the use of cyclic square pressure waves instead of a constant pressure. These square wave pressure pulses result in turbulences and instabilities at the membrane surface which help to reduce the effect of concentration polarization by mixing the water within the concentration polarization boundary layer near the membrane wall. This process enhances the permeate flow rate by reducing the resistance caused by the concentration polarization boundary layer. At the same time, the potential for fouling at the membrane wall is reduced as the foulants that may accumulate at the membrane wall are remixed with the bulk solution.

There have been several recent works on the unsteady operation of RO. Pilipovik and Riverol [1] presented a study on several production process for reduced-alcohol beverages by applying reverse osmosis. They reported that beverages with higher pH produce concentration polarization phenomena such that the fouling in the membrane is increased and the solute flux is reduced considerably. Robertson et al. [2] developed a computer simulation using dynamic matrix control (DMC) algorithm to control a reverse osmosis desalination pilot plant. It was concluded that DMC approach allows substantial improvement over proportional-integral control based on the integral square error. Assef et al. [3] developed an experimental investigation of constrained model predictive control for reverse osmosis desalination unit. The objectives are to produce the specified flowrate of permeate, having the desired salt content, subject to the constraints that the inlet pH and the trans-membrane pressure are within specified bounds. Alatiqi et al. [4] implemented a control system based on system identification, relative gain array and controllability test to control various parameters such as permeate flux and conductivity in reverse osmosis desalination plant. Sobana and Panda [5] implemented model-based controls for simulation of reverse osmosis desalination process for both servo and regulatory problems. Two control schemes were adopted, multiloop internal model control-proportional integral controller under centralized scheme and multivariable PI controller with decoupler under decentralized scheme. Zilouchian and Jafar [6] discussed recent innovation and technological advances in the design and implementation of soft computing methodologies for desalination processes. Those methodologies include fuzzy logic, neural network, generic algorithm and probabilistic reasoning. Jafar and Zilouchian [7] proposed a neural network architecture based on adaptive fields and a learning algorithm that combines both supervised learning of centers and unsupervised learning of output layer weights. This technique was implemented to predict product quality of a reverse osmosis desalination plant. A DMC with/without constraints was used for the control of a simulated reverse osmosis desalination unit, based on a hollow-fiber membrane [8]. The study has addressed two cases. In the first, the permeate flux was controlled by manipulating the feed pressure. The second was a multivariable case in which both the permeate flowrate and conductivity are controlled by adjusting the feed pressure and pH. Zamani et al. [9] reviewed various methods that have been used for introducing unsteady shear at the membrane surface, using unsteady operation to reduce the concentration polarization effect and fouling. An earlier review of unsteady operation for membrane processes was presented by Al-Bastaki and Abbas [10]. Al-Bastaki and Abbas [10,11] also conducted a modeling and experimental work on the effect of cyclic operation of RO based on previous work by Kennedy et al. [12] and Winzeler and Belfort [13]. Other methods of oscillating flow (other than oscillating pressure) have also been used by other workers, such as oscillating membranes in the work of Gomaa and Rao [14]. The implementation of oscillating pressure in an actual industrial process can be practically achieved via the process control system in an RO process. Gao et al. [15] used process control to integrate the operation of ultrafiltration (UF) and RO and use the RO concentrate for the backwash of the UF while the UF filtrate is used as the feed to the RO. Bartman et al. [16] developed a model predictive control algorithm applied to a high capacity reverse osmosis membrane desalination process simulation utilizing feed flow reversal in order to prevent reverse scale crystal formation on the membrane surface. Emad et al. [17] studied the effect of forced periodic operation of a tubular reverse osmosis process through simulation by implementing a nonlinear model predictive control algorithm to regulate the amplitude and period of sinusoidal function that formulate the input signal. Lee et al. [18] developed an optimal control to maximize the permeate production by joint control of the duty of the high pressure pump and the openness of the retentate valve.

Fouling of RO membrane has been extensively addressed in the literature. A number of review papers have discussed the various types of fouling, such as particulate/colloidal fouling, scaling, organic fouling, biofouling and discussed techniques to mitigate fouling such as membrane modification, operating condition optimization and feed treatment [19–23]. Another study presented ultrasound as an effective tool for membrane flux enhancement and membrane cleaning [24]. Tan et al. [25] analyzed fouled RO membrane in a pilot-scale desalination system of biologically treated dyeing wastewater with or without injection of non-oxidizing biocides. Tow et al. [26] presented a comparative study of fouling and scaling in reverse osmosis, forward osmosis and direct contact membrane distillation.

Li et al. [27] studied the removal of pharmaceutically active compounds by fouled nanofiltration and reverse osmosis membranes where NF/RO membranes were fed with both synthetic and real (secondary effluent) water. Warsinger et al. [28] developed a framework for predicting reverse osmosis fouling by comparing the fluid residence time in batch and continuous reverse osmosis systems to the nucleation induction times for crystallization of sparingly soluble salts.

The objective of the current work was to use automatic control to implement square-wave cyclic operation as a mitigation technique for fouling mitigation which could be detected by a significant drop in the permeate flow rate as well as considerable increase in the conductivity. In order to prevent damage to the equipment, particularly the control valves, the square wave cycles are introduced only for a short period of time and at specific frequencies, after which normal steady-state operation is resumed. The aims of the current work could be summarized as follows:

- To verify that using variable square wave pressure superimposed on a study state pressure can improve the permeate flowrate.
- To show that superimposing a square wave pressure on a nominal steady-state pressure cycle with consecutive different cycles with different time periods can be easily adopted in an existing industrial DCS or PLC-controlled RO process to achieve the target of cleaning the membrane, using the disturbance caused by the pulsating pressure regime.

2. Experimental setup

The RO system used in this work was a laboratory-scale RO unit with a single FilmTech BW-30-2540 membrane. The RO unit was equipped with rotameters and pressure gauges for visual observations of flow rate and pressure. To apply square wave cyclic pulses, the unit was modified to be fully automated. This section discusses the instrumentation installed and how the unit was interfaced to the DCS. After installation of the required instrumentation, each of the instruments was interfaced to the Yokogawa DCS. The DCS Hardware such as the Input-Output (I/O) modules. To achieve accurate control, accurate measurements of the process variables (PVs) are required. The PVs which were desired to be measured were pressures and flow rates. Control valves were required to manipulate the flows. Two Yokogawa EJA 430A pressure transmitters, one at the inlet of the RO membrane, to measure the feed pressure and one at the reject to measure the reject pressure, were installed, with an output of 4–20 mA analog signals. Two Gems FT-110 turbine flow sensors were installed to measure the feed and reject flow rates. The flow sensor output was a frequency output which is too fast to be captured by the DCS. To overcome this problem, an electronic conditioning circuit was designed to convert a 50–550 Hz frequency range delivered by the flowmeter and corresponding to the flow to a current range of 4–20 mA, which could be easily read by the DCS was designed. Globe control valves (Burkert 2712), which are best suited for regulatory control, were installed on the feed and reject lines. These control valves operate with pneumatic actuators and digital positioners with input signals in the range of 4–20 mA. Table 1 shows the equipment installed on the RO process with brief specifications of each.

As shown in the wiring diagram in Fig. 1, all of the instrumentation is hard wired to the I/O modules using shielded Siemens process control cables. The analog input module on the DCS field control station is Yokogawa YAAI143-H which accepts 4–20 mA or HART signals from the transmitters. Standard 4–20 mA was selected for this application. The analog output module sends the control signals as 4–20 mA current signals. Each instrument is assigned a specific channel which is used for identifying the instrument while configuring the I/O in the Centum VP. To visualize the process, dynamic graphics of the RO were generated.

Table 1
Process equipment list

S.No.	Equipment	Manufacturer/type	Brief specifications
1.	RO membrane	Filmtech®	Membrane – polyamide thin film composite
		BW-30-2540	Maximum operating temperature and pressure – 45°C and 600 psi
		Spiral wound type	Maximum feed flowrate – 16 gpm
2.	High-pressure pump	CAT® pumps	Reciprocating three rod plunger pump
		2SF29SEEL	Inlet and outlet pressure: 50 and 225 psig
		Positive disp. type	Flow @ 1,425 rpm ≈ 10 Lpm
3.	Feed pump	Lowara – Italy	Stainless steel pump – power: 0.9 kW
		CEAM120/5/A	Single impeller centrifugal – feed pressure – 50 psi
4.	Stirring pump	Brook Crompton	Electric motor – TDA71-MB – 0.75 hp
5.	Pre-filters	Aqua match filters	Max pressure – 125 psi
6.	Pressure (PT01 and PT02) transmitters	Yokogawa®EJA 430A	Range: up to 900 psi
			Output signal: 4–20 mA or HART
7.	Flow transmitters	Gems® FT-110	Range: 1–10 Lpm
	FT01 and FT02	Turbine	Freq. output – 55 to 550 Hz
		Flow sensor	Output signal: 4–20 mA
8.	Inlet control valve	Burkert® 2712	2/2 way globe valve ½” with pneumatic actuator top control 8630 smart positioner
	(CV101)	TopControl® 8630	
		Globe Valve	Power input – 24VDC
			Input signal: 0/4-20 mA or 1-5/10 V or ProfiBUS
9.	Reject control valve	Fischer® +GF+	Ball valve with electrical actuator EA 42
	(CV102)	EA 21 or 42	And PE 25 positioner
		Ball valve	Power input – 100/220 V
			Input signal: 0–10 V or 4–20 mA

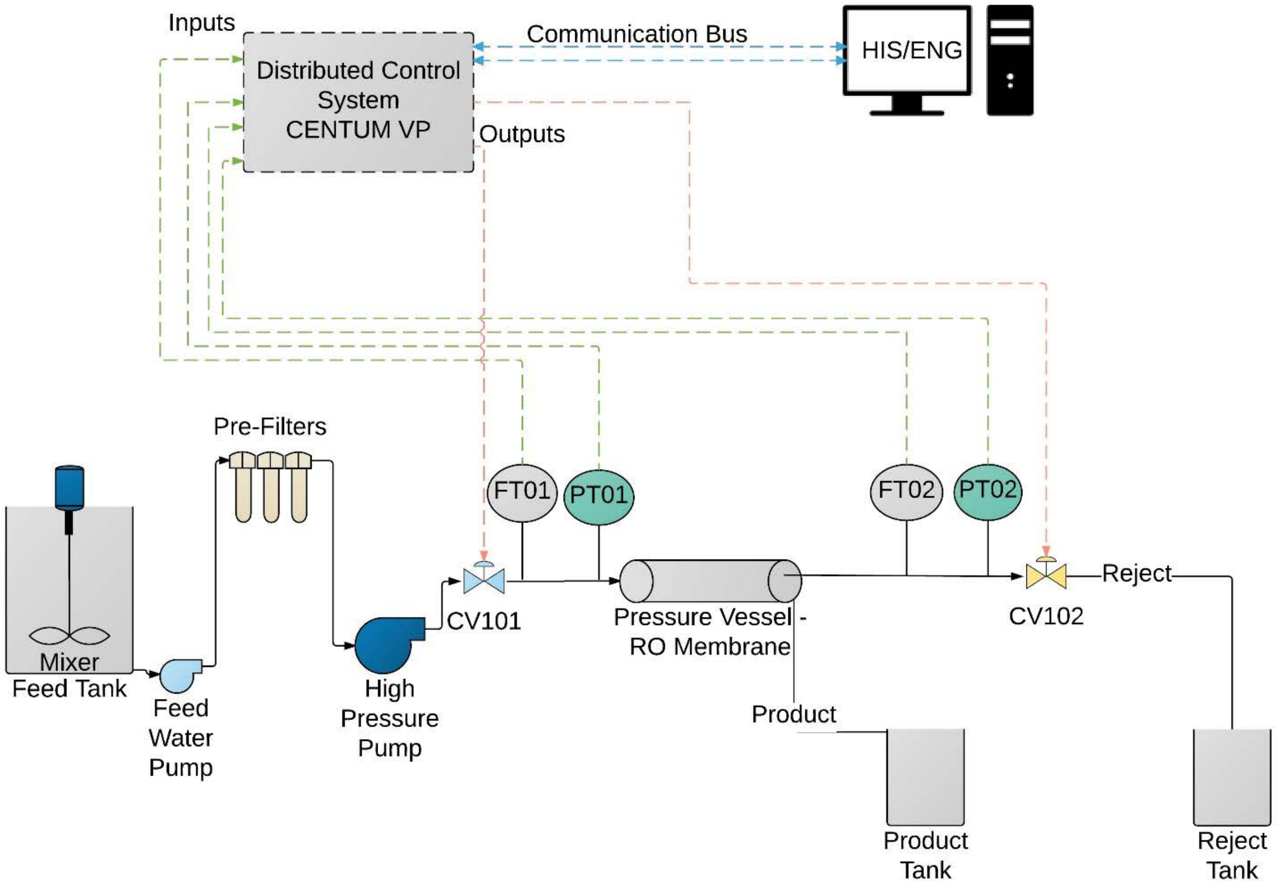

Fig. 1. Reverse osmosis process schematic with its interface to the DCS.

A positive step test was performed to fit the response to a FOPTD transfer function. A negative step test was performed in order to calculate an average transfer function with response. The transfer function relating the permeate flow (Qp) to the reject flow (Qr) exhibited a negative gain of –0.98445 with a time constant of 0.50555 min and a time-delay of 0.50445 min.

$$\frac{\mathrm{Qp}}{\mathrm{Qr}} = \frac{-0.98.e^{-0.5S}}{0.05s+1} \tag{1}$$

3. Experimental procedure and development of application for cyclic operation

This section discusses the logic-based program, used to induce square wave pressure fluctuations for a designated short period of time. The program is based on the temporary cycling which in turn is based on on-delay timer. The latter is a software timer used to generate an output pulse as a result of applied input voltage. The output of the timer is only energized after the required time has elapsed after the input has gone high and stays there until the input coil resets, the timer resets with it. If the input is removed before time out, the time delay resets. To generate a train of square waves, two timers are connected in cascade where the first one drives the second and the second is inverted and drives the first. To obtain a square wave at a particular frequency, a time constant for both timers is loaded to both of them. This time constant is programmable and can be changed according to the requirement. For the frequency generator (set of timers) to work, it has to be enabled (EN) (Fig. 2). To produce four different train of pulses with different frequencies, four different circuits are configured each producing particular cycling frequency. First generator produces 60 s high 60 s low, the second produces a 30 s high 30 s low, the third produces 15 s high 15 s low and the fourth produces 5 s

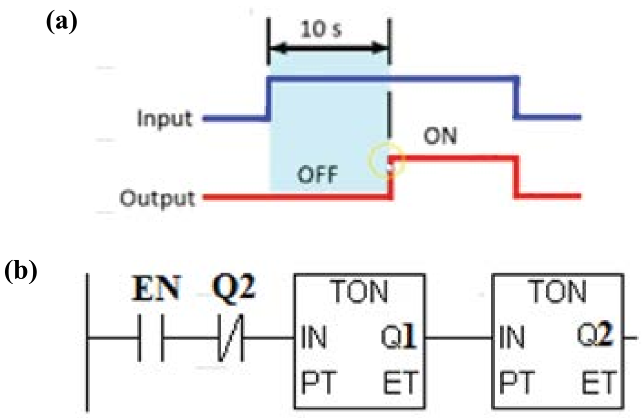

Fig. 2. On delay timer: (a) chronology and (b) circuit.

high 5 s low. Those frequencies are added to produce a pseudo-random binary signal (PRBS). This PRBS is superimposed on nominal operating pressure. The circuit to produce such sequence is shown in Fig. 3.

The pressure pulses were induced by sending a signal to the control valve to suddenly open/close within a specified range by which the pressure applied on the membrane was controlled. The fluctuating pressure operation was performed at four different square wave periods; 2 × 60 s, 2 × 30 s, 2 × 15 s, and 2 × 5 s with a high pressure of 300 psi and a low pressure of 260 psi. The duration of the periodic operation for 2 × 60 s period was 10 min and 5 min for the other three. The RO process was operated at a constant pressure of 280 psi prior to the periodic operation to identify a reference point of the permeate flow rate, which is an indication of the current membrane condition. After the periodic operation, the RO process was operated at the reference point pressure of 280 psi, to identify any improvements in the permeate flow rate.

The DCS software used for regulatory control was modified to add the logic-based program to send signals to the control valve to introduce the square wave functions. The function blocks which initially consisted of the regulatory PID control algorithm were modified to incorporate square wave fluctuations in the opening/closing of the reject control valve. It was desired that this operation be automatically performed for specified duration without interrupting the regulatory control, therefore the temporary cyclic operation is implemented automatically as will be discussed in the next section. However, it could be easily modified to be initiated on-demand by the operator through the Human Interface Station of the DCS (HIS). A logic-based program enables this automatic operation as described in the Appendix. The logic program when enabled, performs the whole periodic operation for a time span of 25 min creating the required signals as shown in Fig. 4.

4. Automating mitigation process

An internal switch Z1 was used to start the whole temporary step-wise pressure test. Initially, when Z1 is off, on delay timer N5 is in Out of service mode (O/S), that is, it is not in operation. When Z1 is turned ON, it turns the first timer N5 to AUT mode and the output of frequency generator F1 is enabled using internal switch Z5. The timer N5 counts up to the set value and its status will be changed to CTUP once the time value is reached. When N5 mode is switched to CTUP, an internal switch Z2 will be turned ON. Z2 starts the timer M5 by switching it to AUT mode. When Z6 is turned ON, the output of frequency generator F2 is enabled while also disabling the output of F1. After the time value of the second timer M5 is reached, its status will be switched to CTUP enabling the third timer using internal switch Z3 and also enabling another internal switch Z10 disabling the output of F1 and F2. When Z3 is turned ON, it starts the timer X5 by switching it to AUT mode. It also disables the output of frequency generator F2 by enabling internal switch Z7 also enabling the output of frequency

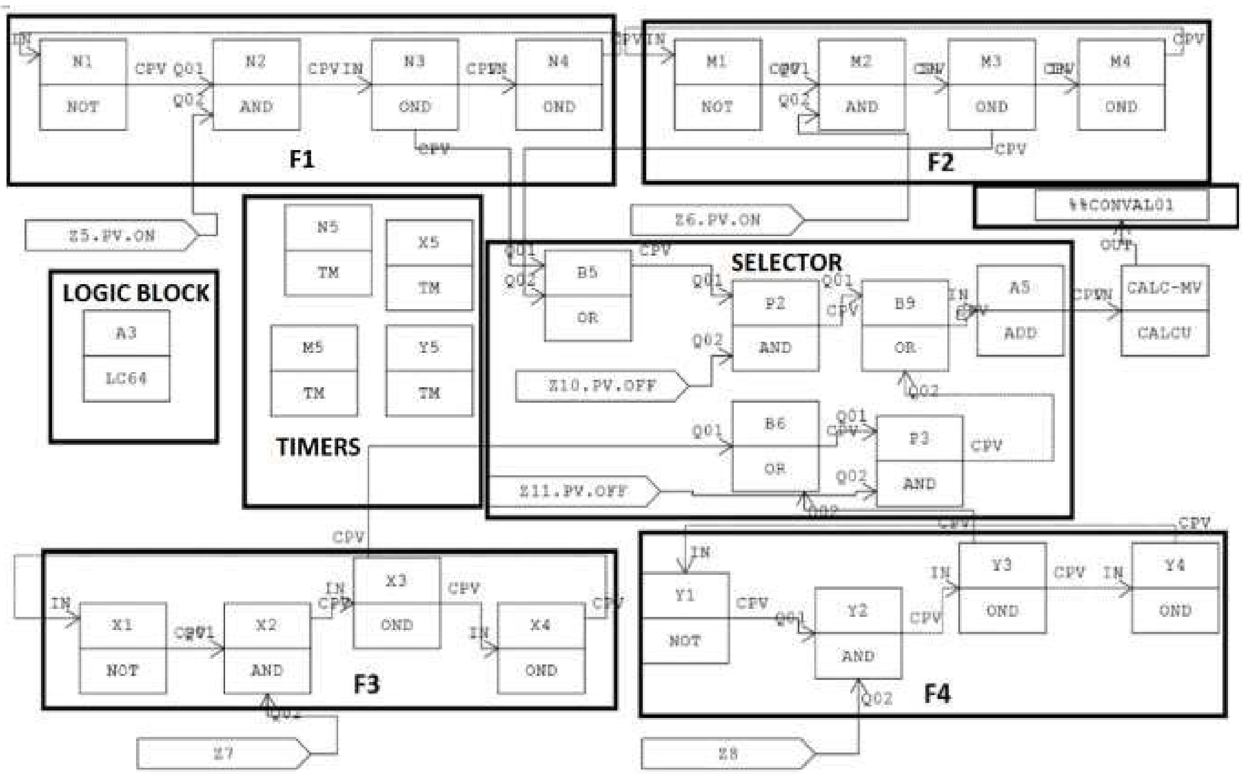

Fig. 3. Control drawing developed using Yokogawa Centum VP with four frequency generators (F1, F2, F3 and F4) to sequentially produce the square wave signals of different cycle periods timed using the Timers (N5, M5, X5 and Y5) whose output is selected sequentially using the Selector block operated by the Logic Chart (A3) and sent to the control valve CONVAL01 (C1).

C1

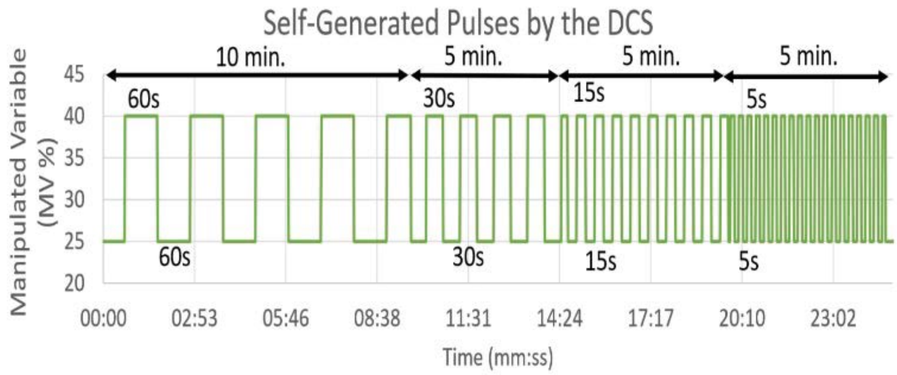

Fig. 4. Square wave signal generated by the DCS with different cycle periods.

generator F3. When the time value of X5 is reached, its status will be switched to CTUP enabling an internal switch Z4. Z4 is used to start the fourth timer Y5 and enable Z8 which will disable the frequency generator F3. After Y5 time value is reached, its status will be turned to CTUP enabling two internal switched Z9 and Z11. Z9 is used to disable the fourth frequency generator and Z11 to disable the outputs of F3 and F4 sent to the OR selector blocks. The signal generated by the above program is shown in Fig. 5 which produced the required pulse signals which were used to change the position of the control valve. To make the system more efficient, the system was modified to automatically trigger the mitigation process whenever the flow rate hits the permissible minimum or the conductivity hits the permissible maximum or both without operation intervention (both are chosen by the operator according to his requirement and could be changed at will). Together with Y5, they drive Z1 which triggers the start of the mitigation process. This is given by Eq. (2) and Z1 is active according to the below table and its realization is shown in the circuit is shown in Fig. 6.

$$Z1 = \left(\mathrm{EC} + \mathrm{Flow}\right) \times \overline{Y5} \tag{2}$$

Inputs			Output
Y5	Flow	EC	Z1
0	1	1	1

5. Results and discussion

The use of square wave pressure pulses results in a disturbance and turbulence in the flow along the membrane surface. This turbulence results in mixing, which reduces the resistance to the permeation of the water through the membrane wall as the concentration at the membrane surface approaches bulk concentration reducing the net driving force. This resistance is caused by the concentration polarization boundary layer, which results in a magnification of the salt concentration near the membrane wall, and hence a magnification of the osmosis pressure. The osmosis pressure acts in the opposite direction to the applied pump pressure forces, hence reducing the net driving pressure force. The mixing imposed by the turbulence caused by the sharp pressure fluctuation results in quick forced convective transportation of the salts and foulants away from membrane wall. Thus, efficient mixing has two beneficial effects, reducing the polarization and, hence, increasing the permeate flowrate, and reducing fouling by moving the potential deposits away from the membrane wall, hence cleaning the membrane wall as well as reducing scaling potential. The scaling potential is increased by increasing concentration polarization, therefore reducing concentration polarization will also reduce possibilities of scaling. For a membrane that has been subject to reversible fouling, for example, colloidal fouling, the results have shown that the sharp pressure fluctuations, administered by high frequency cyclic square pressure waves, were beneficial in mechanical cleaning the membrane as can be seen in the form of increased permeate flow rates after the course of temporary square wave pressure fluctuations. The membrane used in this work was used in many experiments but was not regularly cleaned prior to the experiments conducted in this work. Therefore, the improved permeate flowrate after the use of the temporary square wave course was a result of cleaning of the membrane. Therefore, the technique can be considered as an in-place treatment method that does not require any cleaning chemicals nor stopping the operation.

To test the system, a salt solution of NaCl of 5 g/L (5,000 ppm), with a conductivity of 9.33 ms/cm at 20.5°C, is prepared and filled in the feed tank. The system started where a PID101 is used to control the flow rate using the reject valve. The signal from the transmitter is sent to the PID controller which calculates the error between the set point and actual measurement and sends appropriate control signal to the control valve. Because the system is automatically monitoring the flowrate and the conductivity. When either or both attain the threshold, the mitigation process starts by applying the square wave pressure pulses.

The graphs are to scale. It could be noticed that the inlet pressure slightly decreases with time for two reasons:

- The pressure decreases with time for each frequency band. So, in Fig. 7, where we applied the pressure for 60 s on 60 s off for 10 min, it could be noticed that the pressure drops continuously from 297 to 291 psi. This continues with other bands. For the 30 s on 30 s off for 10 min, the pressure drops from 291 to 288 psi (notice that 291 psi is the continuation of the end of 60 s on 60 s

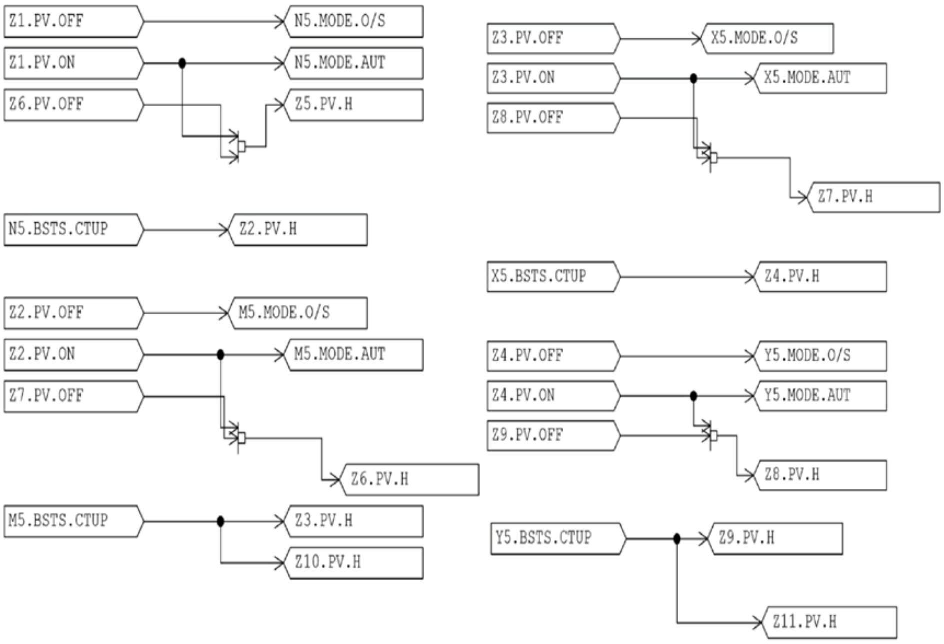

Fig. 5. Program developed using Yokogawa Centum VP to sequentially activate four different square wave generators for each of their specified periods.

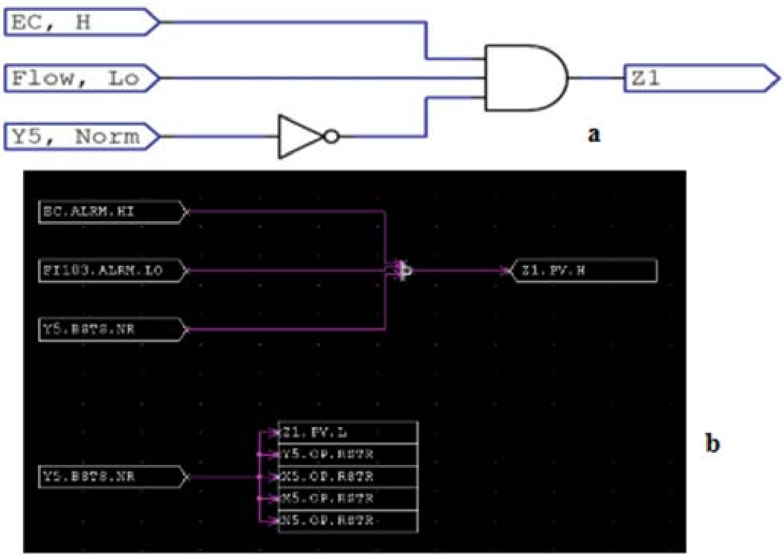

Fig. 6. (a) Circuit diagram to automatically start the mitigation process and (b) implementing automatic mitigation using DCS.

off band) (Fig. 8). Then in Fig. 9 (15 s on 15 s off), the pressure drops from 288 psi (which was the continuation of the 30 s on 30 s off) to about 286PSI. The trend continues with the last trend (5 s on 5 s off) where the pressure drops from 286 to 282 psi (Fig. 10). So as a conclusion, the membrane resistance to input pressure decreases with the cleaning, this results in the drop of input pressure. The reduced inlet pressure requirement may be a result of reduced net driving force which is caused by concentration of the fluid at the membrane surface approaching the bulk concentration reducing overall concentration polarization.

- It could also be noticed that as the pulses get faster with increasing frequency, the response of the control valve gets slower, so it filters out the high frequencies represented by the fast edges of the square wave, resulting in the sinusoidal pressure wave shape. It could be concluded that if the frequency is increased further, the valve may not respond due to mechanical limitations.

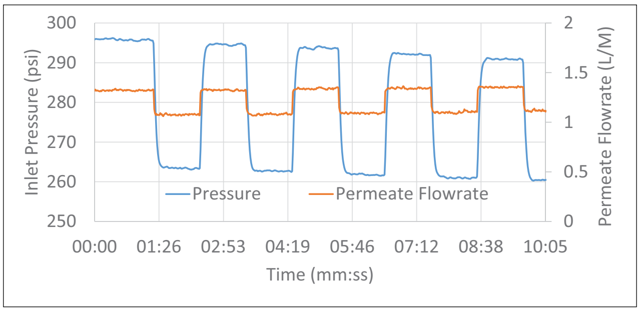

Fig. 7. Step-wise cyclic pressure pulses with sudden changes every 60 s and the response of permeate flow rate.

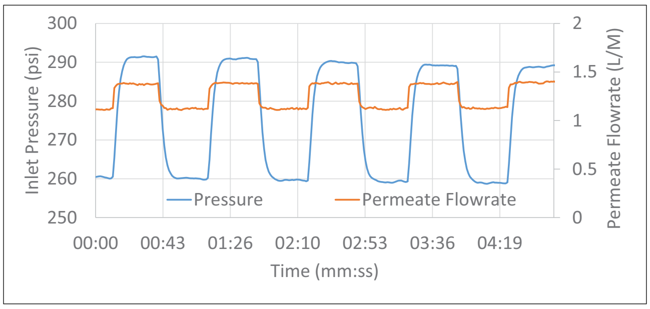

Fig. 8. Step-wise cyclic pressure pulses with sudden changes

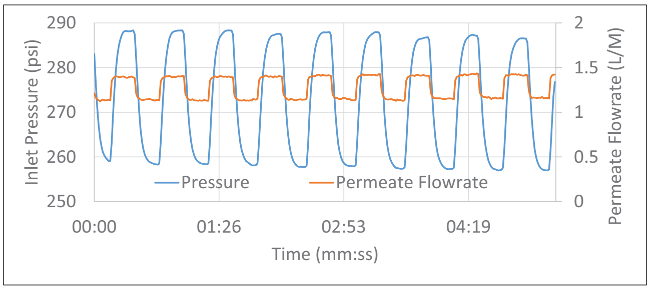

Fig. 9. Step-wise cyclic pressure pulses with sudden changes every 15 s and the response of permeate flow rate.

The resulting square wave pressure pulses improved the permeate flowrate significantly. As shown in Figs. 7–10, the appropriate square wave pressure pulses that were introduced by the DCS resulted in a gradual increase in the permeate flow while oscillating with the square wave pressure pulses. A further increase in this permeate flow was observed as the time period of the square wave shortened. It can be seen that the average permeate flow rate for all of the four time periods is higher than the average permeate flow of the initial reference point run. For the constant pressure runs of the RO process at 280 psi, the average pressure of the high and low limits of the square wave pressure pulse, performed before and after the periodic operation indicated a 28.7% increase in the permeation rate after the periodic operation as shown in Fig. 10. This increase in the permeate flow is at the same pressure after the periodic operation. This indicates that the membrane performance has improved after the application of the temporary square wave operation.

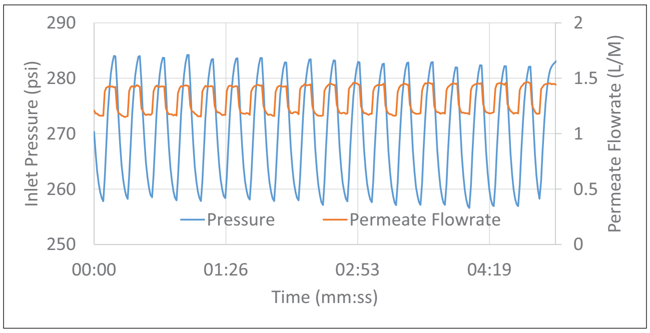

Fig. 10. Step-wise cyclic pressure pulses with sudden changes every 5 s and the response of permeate flow rate.

A reasonable explanation could be that the fluid instabilities and turbulence that may have been created during the square wave cyclic operation has resulted in cleaning the membrane surface. A variation of the permeate flow as a function of the square wave periods is seen in Fig. 11. It shows that the permeation rate increases with a decrease in the time period of the square wave or with an increase in the frequency. The permeate flow rate can be increased by reducing the time period further. However, a high frequency square wave signal can be detrimental to the durability of the control valves and other instrumentation. As a result, it is safe to say it is not recommended to go below 5 s low 5 s high pulse. This could be noticed from the response from Fig. 10 where the pressure is no longer square but very close to a sinusoidal.

The desalination process was run. Once the system settled down, the mitigation course was introduced by switching the soft switch Z5.PV.ON on where a frequency of 60 s on 60 s off for 10 min as shown in Fig. 7. It is clear from the figure that the permeate flow rate follows the change of the pressure. This generator is turned off automatically and generator 2 which produces a frequency of 30 s on 30 s off is turned on through Z6.PV.ON for 5 min as shown in Fig. 8. By comparing Figs. 7 and 8, it could be noticed that the permeate flow rate has increased considerably indicating the effectiveness of the mitigation process. After that Z6.PV.ON is automatically turned off and at the same time, Z7.PV.ON is turned on for 15 min and the cycling is shown in Fig. 9. Here two things could be noticed, the small increase of the flow rate and the effect of filtering of the pressure. Finally generator 3 (F3) is automatically turned off and generator 4 (F4) is switched on for 5 min at a frequency of 5 s on 5 s off. The response is shown in Fig. 10. It is clear that there is a small increase in the permeate flow rate but both the pressure response and the valve are filtering the high frequencies in the pulses because the signal is too fast for the membrane and the valve to respond quickly enough. At the end of the mitigation run, it was noticed that the pressure almost stayed constant around 278 psi as shown in Fig. 11, but the flow rate has increased considerably as shown in Fig. 12. At the end of the full run, it was found to be increased approximately by 28.2%. Not only that the mitigation has big impact on the quality of the permeate where the conductivity has decreased from 920 to 287 µs/cm (Fig. 13). To enhance the results further, the experiment was reconducted on the same RO few months later with the

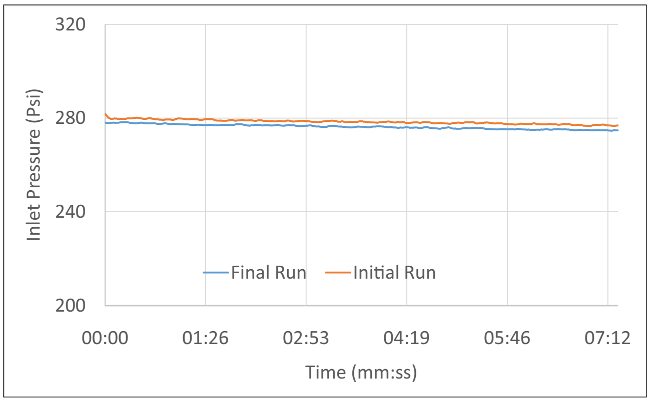

Fig. 11. Initial and final run inlet pressure maintained close to 278 psi.

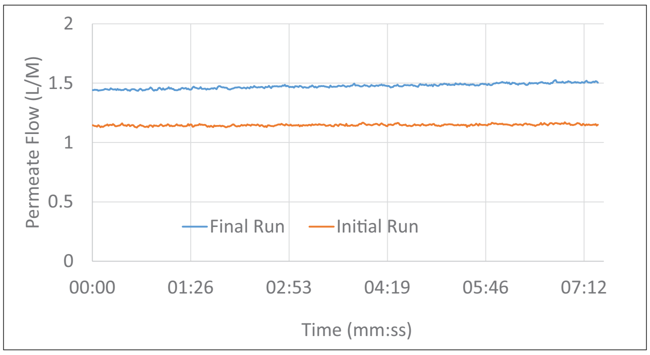

Fig. 12. Initial and final run permeate flow rate, as shown an improvement is detected.

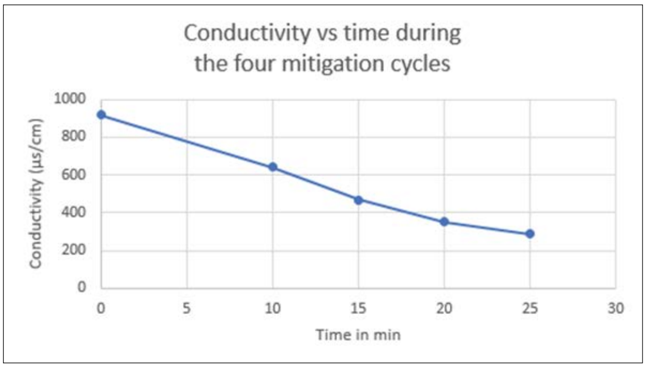

Fig. 13. Permeate conductivity reduction during the four fouling mitigation cycles.

same specifications, that is, NaCl solution with 5,000 ppm and the results shown in Fig. 14 were obtained. It shows clearly the effect of the temporary cycling on improving the permeate flow rate where the flow rate increased by about 16% and confirms the previous results. To enhance further the analysis of the effect of the cycling on mitigation, a second RO with a 1.05 m^2 membrane CH87 with membrane film-Tec LO model BW30 2521 was used. An NaCl solution was prepared where the concentration was 2,000 ppm, and conductivity of the feed is 1.021 ms/cm and

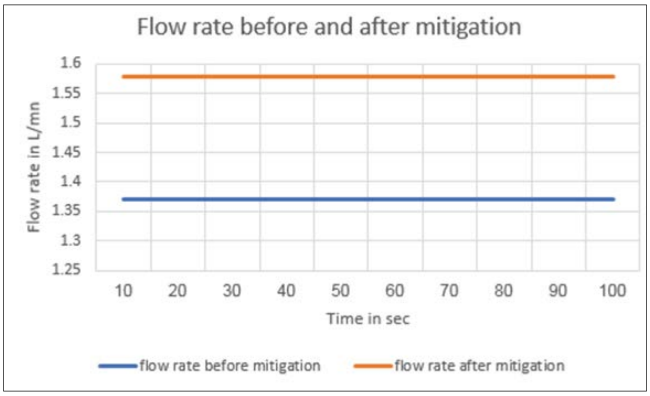

Fig. 14. Comparison of flow rate before and after mitigation taken few months from the first run shown in Fig. 12.

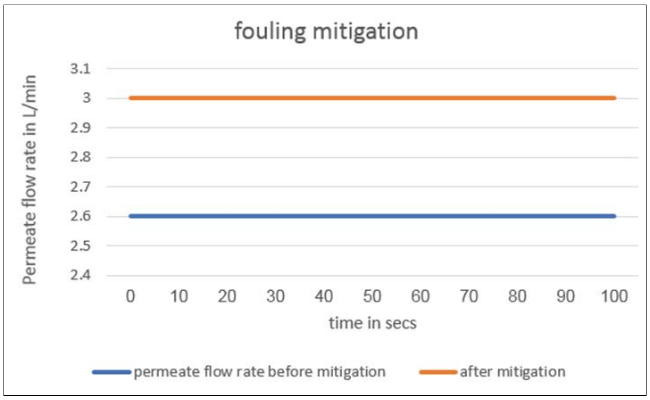

Fig. 15. Permeate flow rate for RO H87 with membrane Film-TEC model BW30 2521.

that of the reject 8.04 ms/cm. The same cycle was applied. Both permeate flow rate and permeate conductivity were measured. At the beginning, the flow rate was 2.6 L/min and the permeate conductivity was 1,021 µs/cm. At the end of the run, the product flow rate had increased to 3 L/min, which is an increase of about 15.4% (Fig. 15) and the conductivity came down to 477 µs/cm from 1,021 µs/cm, indicating not only an increase in the permeate flow rate but the quality of the water by decreasing its conductivity.

6. Conclusions

This study has shown promising results for fouling mitigation and reduction in concentration polarization without interruption of production with reduction in cost where the membrane life could largely be extended. The study showed that an increase in permeate flowrate up to 28.7% could be achieved. Another advantage is that the study has shown considerable reduction of permeate conductivity, where for only 25 min of mitigation time, the conductivity has come down from 950 to about 250 µs/cm. Certainly, if the mitigation time is extended more, flowrate and conductivity improve considerably. It was also noticed that there is a limit on the mitigation cycle where a frequency less of 5 s on 5 s off introduces filtering effect either on the pressure or the valve action due to the big time constants.

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Appendix

In order to send square wave signals to the control valve, a frequency generator was employed with specified operation time. The periodic operation was performed in one go with the help of this program by testing all of the four time periods of the square wave signals in a span of 25 min of operation of the RO process. To enable this, four frequency generators were required for the complete operation. Each frequency generator consisted of two on-delay timers, one not-logic operator, one and-logic operator, and one soft-switch. The principle of operation of each frequency generator is discussed as shown in Fig. 3; the time delay value of the on-delay timer1 (N3) and on-delay timer2 (N4) was set to 60 s. Timer N3 outputs a high signal after the 60 s have elapsed and it will trigger the count of timer N4, which will wait for another 60 s and then output high. A negated output of timer 2 (N4) was used to drive timer 1 (N3) continuously creating a continuous on off square wave signal with a period of 60 s. A bias signal was added to this binary signal to change the amplitude of the pulse so that the upper and lower limit of the valve movement can be defined such as 40% to 25% and then 25% to 40% repeatedly. Therefore, if the whole frequency generator is assumed to be a single block (F1), it could be enabled or disable by the operated using soft-switch (Z5). Frequency generators for the other three time periods 30, 15 and 5 s were created similarly each of which operated with a dedicated soft-switch. To enable a smooth sequential operation of all the frequency generators, a logic program was developed (LC64; Fig. 4) thus sending appropriate signals to the control valve (CONVAL01).