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Significant energy savings by optimising membrane design in multi-stage reverse osmosis wastewater treatment process

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Abstract

The total energy consumption of many Reverse Osmosis (RO) plants has continuously improved as a result of manufacturing highly impermeable membranes in addition to implementing energy recovery devices. The total energy consumption of the RO process contributes significantly to the total cost of water treatment. Therefore, any way of keeping the energy consumption to a minimum is highly desirable but continues to be a real challenge in practice. Potential areas to explore for achieving this include the possibility of optimising the module design parameters and/or the associated operating parameters. This research focuses on this precise aim by evaluating the impact of the design characteristics of membrane length, width, and feed channel height on the total energy consumption for two selected pilot-plant RO process configurations for the removal of chlorophenol from wastewater. The proposed two configurations, with and without an energy recovery device (ERD), consist of four cylindrical pressure vessels connected in series and stuffed with spiral wound membranes. A detailed steady-state model developed earlier by the authors is used here to study such impact via repetitive simulation. The results achieved confirm that the overall energy consumption can be reduced by actually increasing the membrane width with a simultaneous reduction of membrane length at constant membrane area and module volume. Energy savings of more than 60 % and 54 % have been achieved for the two configurations with and without ERD respectively using process optimization. The energy savings are significantly higher compared to other available similar studies from the literature.

***Keywords*:** Reverse Osmosis (RO); Spiral-wound Module; Chlorophenol Removal; Energy Consumption.

1. Introduction

Chlorophenol and phenolic compounds (aromatic compounds) are considered as one of the common pollutants that can be found in effluents of several industrial processes such as, refineries, fertilizers, petrochemical, pharmaceutical and lubricant production, which are reported as having high toxicity even at low concentrations.[1] Most importantly, the existence of a small trace amount of such high-toxic compounds in industrial effluents can prohibit the reuse of water in many applications. High-pressure driven membrane technology is widely used for making high quality water from seawater and wastewater. Interestingly, it appears that the extent of energy consumption of the RO process has been steadily improved due to the development of high permeability membranes in addition to incorporating the energy recovery devices.[2] Most specifically, the total energy consumption used to drive the high-pressure pumps is considered as the main constitute of total cost of water desalination.[3] Significant research from academic and industrial societies are made towards the reduction of energy consumption of the RO process by optimising the operating conditions, investigating the number of stages, modules configuration, implementing an energy recovery device (ERD) and membrane type.[4-7]. However, there are some examples in the literature that highlighted the membrane characteristics optimisation and its effect on the total energy consumption of an individual module of the RO process as follows:

Sablani *et al.* [8] analysed the influence of spacer thickness of the spiral wound membrane module on the permeate flux of the RO seawater desalination process. They found that there is a specific intermediate spacer thickness, which yields the highest economic performance compared to other feed spacers tested. Karabelas *et al.* [9] studied the optimisation of a spiral-wound RO seawater and brackish desalination system operation by measuring the sensitivity of varying the element design variables, including feed and permeate spacer characteristics (channel gap) and sheet width (at a constant total area), on the operating variables including permeate flux, trans-membrane pressure, retentate and permeate pressures, and feed velocity. Their optimisation results showed that the permeate-side variation affected the trans-membrane pressure and module productivity directly. It was also found that the retentate-side spacer could be used to control the pressure drop across the element, and that the overall performances of low and high-pressure membranes are increased when using short sheets of membrane. Sharifanfar *et al.* [10] affirmed that the recovery rate of the pomegranate juice clarification process is significantly affected by the size of the feed canal height of microfiltration membrane. Gu *et al.* [11] investigated the impact of the height of both feed and permeate channels, membrane dimensions and centre pipe radii, on the performance and energy consumption of a spiral-wound RO desalination process. While Al-Obaidi *et al.* [12] optimised the energy consumption of an individual spiral-wound RO module for the removal of dimethylphenol from wastewater. They achieved this by manipulating the module dimensions including membrane length, width, and feed channel height. The net outcome of this is that the energy consumption has been reduced by 19.2 % in comparison with the standard module measurements. To the best of authors' knowledge, the impact of membrane design characteristics of multi-stage RO wastewater process on energy consumption has not yet been explored fully and therefore requires further research. The aim of this paper is to attempt this challenge by studying several repetitive optimisation scenarios to examine the impact of varying the membrane and module specifications on the overall energy consumption and recovery rate of a multi-stage RO process for the removal of chlorophenol from wastewater. This will be carried out by studying the consequences of altering the membrane dimensions (length and width) at constant area, and feed channel height at a varied module volume, as well as increasing the membrane area outside the manufacturer's specification. A further investigation is carried out to specifically explore the outcomes of two proposed configurations of membrane design with and without ERD on the total energy saving. The starting point of this research is to explore if even more potential energy can actually be saved by optimising the membrane dimensions of multi-stage RO process beyond what has already been achieved by Al-Obaidi *et al.* [12] in an individual RO module but this time for the removal of chlorophenol.

The model of Al-Obaidi *et al.* [12], which included the thermodynamic and mass transfer properties of chlorophenol, can readily be adapted for use in this research. The model has already been validated against experimental data obtained for the removal of dimethylphenol in an individual membrane pilot-plant. The detail of this model and the thermophysical properties of chlorophenol are given in Tables A.1 and A.2 in Appendix A for convenience. Moreover, the model has been validated taking into consideration the experimental results of Sundaramoorthy *et al.* [13] for the removal of chlorophenol from wastewater using an individual RO membrane module. The validation results of this study are given in Table A.3 in Appendix A, which show a good match between the model prediction and the experimental data. Finally, the model is further tailored by including Eqs. (17) and (18) (shown in Table A.1 in Appendix A) to consider the calculation of the energy consumption for each proposed configuration (A and B) of the multi-stage RO process shown in Fig. 1.

Fig. 1. Schematic diagram of two tapered configurations A and B of the RO pilot-scale plant.

2. Plant description and feed characteristics

This section describes the characteristics of the two proposed configurations of the multi-stage RO wastewater pilot-plant. Fig. 1 shows the schematic diagrams of configurations A and B, each containing four series pressure vessels (three stages) stuffed with spiral wound modules using the membrane type Ion exchange, India of 7.845 m^2. Stage 1 contains two parallel modules while one module designed for stages 2 and 3. The design of retentate reprocessing is used where the permeate of three pressure vessels is blended to form the product stream. The technical details of the membrane used in the two configurations are identical to those used by Sundaramoorthy *et al.* [13], where a single element is used to remove chlorophenol from wastewater, as shown in Table 1. Configurations A and B are similar except that B has an energy recovery device (ERD) and booster pump (BP), both used to reduce the overall energy consumption. Moreover, the feed stream is split into two parts. The first part is directly pumped using a high-pressure pump (efficiency 85 %), which can deliver a maximum operating pressure of 20 atm. The second part is fed back to the ERD (efficiency 80 %) to raise its pressure using a high-pressure retentate stream. More specifically, ERD is used to transfer the energy from the high-pressure retentate stream to the low-pressure feed stream, using a rotary turbine that initiates a secondary pump to pressurize the feed. For operational safety reasons, the inlet streams of ERD of low-pressure feed and high-pressure retentate should be equal. Most importantly, it is necessary to use a booster pump, which can raise the feed stream to the required operating pressure. The design of configuration B shown in Fig. 1 is identical to the one by Oh *et al.* [14] in seawater desalination RO process. Finally, the transport parameters of water and chlorophenol and the membrane friction parameter are derived from Sundaramoorthy *et al.* [13] and given in Table 2.

Table 1. Membrane characteristics and geometry of Ion Exchange, India Ltd.*

Table 2. Transport parameters and membrane friction factor

3. Simulation of the RO process

In this section, the RO process of the two configurations A and B with and without ERD (Fig. 1) is simulated using four sets of operating conditions of feed concentration, flow rate, pressure, and temperature as follows:

1. 6.226E-3 kmol/m³, 4.66E-4 m³/s, 11 atm, 29 °C.
2. 6.226E-3 kmol/m³, 4.66E-4 m³/s, 15 atm, 31 °C.
3. 6.226E-3 kmol/m³, 5.166E-4 m³/s, 13.58 atm, 30 °C.
4. 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm, 33 °C.

Please note that the selected sets of operating conditions are within the operating conditions of Sundaramoorthy *et al.* [13] except for the feed flow rate where it is chosen to fulfil the requirements of two parallel modules in the first stage (Fig. 1).

Table 3 shows simulation results of the two configurations considering the total energy consumption, chlorophenol removal, and total water recovery. Moreover, these results are compared to the maximum chlorophenol rejection rate of Sundaramoorthy *et al.* [13] of an individual RO module (Ion Exchange, India) used to remove chlorophenol from wastewater. It is important to note that the maximum performance achieved by Sundaramoorthy *et al.'s* [13] experiment is conducted at operating conditions of 6.226E-3 kmol/m³, 2.583E-4 m³/s, 13.58 atm and 31 °C of inlet chlorophenol concentration, feed flow rate, pressure, and temperature respectively. The results achieved in configurations A and B clearly show that the total recovery rate is higher than that obtained from the individual RO module. It can therefore be concluded that the proposed fixed-size configurations with and without ERD yield more energy saving than the single-stage RO process (Sundaramoorthy *et al.* [13]) with the same membrane specifications. Having said, it is acknowledged that this improvement comes with the penalty of a greater membrane cost. Incidentally, Zhu *et al.* [6] confirm the same findings for the RO desalination process. While Li [7] found that more energy can be saved when increasing the number of stages (no more than five) and using an ERD. It would therefore be interesting to evaluate the impact of module dimensions on the performance of these configurations.

Table 3. Simulation results

4. Impact of design parameters

This part of the research discusses the impact of varying the membrane and module specifications (outside the manufacturer's specifications presented in Table 1) for a given set of operating conditions on the energy consumption, total water recovery, and chlorophenol rejection for the two configurations A and B of Fig. 1. Most importantly, the modification of membrane and module specification is carried out simultaneously for all the modules shown in Fig. 1.

4.1 *Effects of altering membrane width and length concurrently at constant area and module volume*

The membrane dimensions (width and length) of each module for configurations A and B are simultaneously changed when both the volume and membrane area are kept constant, as per the original manufacturer's specification. The initial expectation is that this change will amend the flow patterns associated with the feed fluid within the membrane module.

The geometry optimisation of the membrane type Ion Exchange - India is carried out in the simulated operating conditions of 5.166E-4 m^3/s, 15 atm and 31 °C and initial chlorophenol concentration of 6.226E-3 $kmol/m^3$. The effect of 5 % step change reductions in membrane length (increase the width) at constant area of 7.845 m^2 and module volume (height of the feed channel of 0.8E-3 m) for all the modules of configurations A and B on chlorophenol rejection and total recovery rate is given in Fig. 2. While Fig. 3 shows the impact of membrane width increase at constant membrane area and volume on the energy consumption of configurations A and B.

Fig. 2. Effect of 5 % step change reduction in membranes length at constant membrane area on chlorophenol rejection and water recovery (inlet feed conditions, 6.226E-3 $kmol/m^3$, 5.166E-4 m^3/s, 15 atm and 31 °C)

Fig. 3. Effect of 5 % step change reduction in membranes length at constant membrane area on specific energy consumption of configurations A and B (inlet feed conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

It is not difficult to see that the rejection parameter is gradually decreased due to an increase in membrane width at constant membrane area (Fig. 2). However, an increase in total water recovery is observed as a result of this variation. It is alleged that the reason for this phenomenon is that the reduction of the membrane length results in a decrease of the loss of the operating pressure along the membrane length, which in turn promotes the flux of water and increases the total recovery. Lomax [15] confirmed that shorter sheets with many envelopes (longer width) for a given total membrane area have a clear permeate flux and total recovery advantage. Also, Karabelas *et al.* [9] showed that increasing the membrane width at a constant membrane area improved the performance of seawater RO membrane with a constraint of module diameter that can hold a maximum number of membrane envelops.

Fig. 3 also shows that the reduction of the membrane length yields a reduction in the consumption of energy in both the configurations tested, albeit with an even better result in pilot-plant B. Reducing the membrane length has yielded a maximum reduction of chlorophenol rejection to about 5.18 % with a 5.26 % increase in recovery rate with around 13 % and 5 % energy consumption reduction with and without ERD respectively. These results confirm the advantages of configuration B in energy consumption despite a small decrease in chlorophenol rejection percentage.

4.2 *Effect of altering the feed channel height at constant area and variable module volume*

This section explores the effect of feed channel height on the RO process, since the feed spacers readily come in different thicknesses and geometries. The feed spacers, in turn, influence the rate of turbulence and the fluid flow hydrodynamics. The influence of increasing feed channel height on chlorophenol rejection and total recovery rate is shown graphically in Fig. 4. This readily shows that the feed channel height increases outside the manufacturer's specification despite keeping a constant membrane area but with a variable module volume for all the modules connected as shown in configuration A and B (Fig. 1) at constant operating feed conditions. Fig.

5 shows a similar impact of the feed channel height on the energy consumption of configurations A and B.

Fig. 4. Effect of feed channel height on chlorophenol rejection and total recovery (inlet feed conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

Fig. 5. Effect of feed channel height on energy consumption of configurations with and without ERD (inlet feed conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

Interestingly, Fig. 4 shows that chlorophenol rejection and total recovery rate are decreasing as the feed channel height increases. This in turn retards the energy consumption of both configurations tested (Fig. 5). This is due to an increase in pressure drop caused by increasing the height of the feed channel in addition to a clear reduction in feed velocity caused by increasing the module volume. This causes a reduction in the driving force of water flux and ultimately reduces the rejection parameter. Furthermore, increasing the feed channel height has a significant negative impact on the total recovery in comparison to altering the dimensions of membranes width and length as can be seen in Fig. 2, which improves the total recovery rate. Therefore, increasing the feed channel height from 0.5E-3 to 1E-3 m causes 25.31 % and 30.39 % reduction in rejection parameter and recovery rate respectively, while an increase of the energy consumption of 37.24 % and 43.26 % occurs for configurations with and without ERD respectively.

4.3 *Effect of increasing the membrane area by an incremental increase of membrane dimensions*

This section explores the effect of increasing the membrane area by 50 % of all the modules of configurations A and B (shown in Fig. 1), starting from the original membrane value of 7.845 m² and increasing it incrementally to 11.768 m². This is implemented using the following two options:

1) A 50 % increase in membrane length of 10 % step change with keeping a constant membrane width of 8.4 m and feed channel height of 0.8E-3 m.

2) A 50 % increase in membrane width of 10 % step change with keeping a constant membrane length of 0.934 m and feed channel height of 0.8E-3 m at constant operating feed conditions on chlorophenol rejection, total recovery rate, and energy consumption of configurations A and B is shown in Figs. 6 and 7.

Fig. 6 readily shows that the chlorophenol rejection is kept more or less constant, where it decreases from 81.92 % to 79.34 % at 0.3 % reduction when the membrane area increases as a result of an increase in the membrane length from 0.934 m to 1.4 m. However, a 50 % increase in the membrane, applied by increasing the membrane width from 8.4 to 12.6 m, causes a reduction of about 6.58 % in chlorophenol rejection from 81.92 % to 76.53 %.
Fig. 6 shows that an increase in the membrane area from 7.845 m^2 to 11.768 m^2 causes a considerable increase of 30.90 % from 48.11 % to 62.98 % and 39.76 % from 48.11 % to 67.25 % in total recovery rate as a response to an increase in the membrane width and length respectively. As expected, Fig. 7 shows that an increase in the membrane area in both the options tested causes a reduction in energy consumption. Therefore, the energy consumption of configuration A without ERD decreases by 23.6 % from 1.03 kWh/m^3 to 0.78 kWh/m^3 and 28.44 % from 1.03 kWh/m^3 to 0.73 kWh/m^3 when increasing the membrane area; i.e. by increasing the membrane width and length respectively. On the other hand, the energy consumption of configuration B with ERD decreases by 15.81 % from 0.83 kWh/m^3 to 0.70 kWh/m^3 and 24.08 % from 0.83 kWh/m^3 to 0.63 % when increasing the membrane area; i.e. by increasing the membrane width and length respectively. It can therefore be concluded that a 50 % increase of membrane area due to an increase in the membrane width at constant length is preferable because it has a positive impact on the total recovery rate and energy consumption of the configurations tested (especially B) albeit with a small reduction in chlorophenol rejection of 6.58 %. This is compared to the consequence of increasing the membrane area by increasing the membrane length but with a constant width. The clear feed velocity reduction in all modules is essentially the main reason for 6.58 % reduction in the chlorophenol rejection mainly due to an increase in the membrane width at a constant length. The next step is therefore to investigate reductions of 37.66 %, 46.89 % and 50.05 % in feed velocity of stages 1, 2 and 3 respectively after the 50 % increase in the membrane width at constant length. These will be compared to similar reductions of 6.62 %, 19.47 and 26.04 % due to 50 % increase in the membrane length at

constant width. The rationale here is that this process increases the accumulated chlorophenol at the membrane wall and it therefore increases the permeate concentration as a result of an increase of the solute flux through the membrane.

Fig. 6. Effect of 50 % membrane increase caused by separate membranes length and width increasing on chlorophenol rejection and total recovery rate (initial conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

Fig. 7. Effect of 50 % membrane increase caused by separate membranes length and width increasing on energy consumption of configurations of with and without ERD (initial conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

Fig. 8 shows the progress of permeate concentration for the two scenarios of increasing the membrane area due to an increase in the membrane length and width respectively. It can readily be seen that an increase in the membrane area due to an increase in the membrane width has a higher passive impact on the permeate concentration of all the stages. Moreover, the gain of total water recovery after increasing the membrane width at constant length is higher than what can be achieved after increasing the membrane length in constant width. This is because of higher pressure loss occurs in all the modules as a result of an increase in the membrane length at a constant width compared to the second scenario. This causes a reduction of the quantity of water, which penetrates the membrane compared to the original membrane length. Simulation results for this scenario show a total reduction of 20.47 % occurring in the outlet plant pressure after a 50 % increase in the membrane length of each module, compared to 17.45 % reduction after a 50 % increase in the membrane width. It can therefore be concluded that more reduction of energy consumption in the two configurations with and without ERD can be achieved by increasing the membrane area based on an increase in the membrane width at constant length (Fig. 7).

Fig. 8. Effect of 50 % membrane increase caused by separate membranes length and width increasing on chlorophenol permeate concentrations at the three stages rejection (initial conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

4.4 *Effect of increasing the membrane area by a synchronous increase of membrane length and width*

This section explores the influence of increasing the membrane area on the performance of a multi-stage RO process for removing chlorophenol from wastewater. More specifically, the area is increased by 50 % by synchronously increasing the membrane length and width of all the modules at the constant original manufacture's feed channel height of 0.8E-3 m.

The simulation results shown in Fig. 9 confirm 4.82 % reduction in chlorophenol rejection but 36.42 % increase of total water recovery as a result of increasing the membrane area by 50 %. The simulation results shown in Fig. 10 show 20.97 % and 26.69 % reduction of total energy consumption for configurations A and B; i.e. with and without ERD respectively. It can therefore be concluded that an increase of the membrane area yields less energy consumption but also reduced chlorophenol rejection. It can be concluded furthermore that increasing the membrane area by 50 % by increasing the membrane width at constant length and feed channel height yields higher reduction of energy consumption in comparison to increasing the membrane length and synchronously increasing membrane length and width in both configurations.

Fig. 9. The effect of 50 % membrane increase caused by the synchronous membranes length and width increasing on chlorophenol rejection and total recovery rate (initial conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

Fig. 10. The effect of 50 % membrane increase caused by the synchronous membranes length and width increasing on energy consumption of configurations of with and without ERD (initial conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

Clearly the interplay between the total energy consumption and the chlorophenol rejection will need further investigation. This is the subject of the next section, which discusses a multi-objective optimisation study using the gPROMS software.[16] This study concurrently explores the impact of all the membrane dimensions while maximising the reduction of energy consumption and chlorophenol rejection for the two proposed configurations, with and without ERD.

5. Optimisation results of the two RO process configurations with and without ERD

This is carried out using the gPROMS optimisation tool, where the minimisation of the energy consumption and maximization of the chlorophenol rejection are considered to be the objective functions at the selected operating conditions of 6.226E-3 kmol/m^3, 5.166E-4 m^3/s, 15 atm and 31 °C of feed chlorophenol concentration, feed flow rate, pressure, and temperature respectively. The module dimensions of all the membranes including; length, width, and feed channel height are considered as the design parameters selected within upper and lower limits shown in Table 4. Since the membrane type used in this simulation is Ion Exchange, India, the value of the area of 7.845 m^2 is set as a constraint.

The non-linear algebraic model equations shown in Table A.1 of Appendix A are written in the following compact form:

$f(x, u, v) = 0$, where:

- x is the set of all algebraic variables,
- u is the set of decision variables (to be optimised), and
- v denotes the constant parameters of the process.

The function f is assumed to be continuously differentiable with respect to all their arguments.

Table 4. Limits of optimisation operational parameters

The optimisation problem will be mathematically written as follows:

- Given: Operating feed parameters, module specifications.
- Optimise: Membrane dimensions.
- Minimise: The total energy consumption.

- Maximise: The chlorophenol rejection.
- Subject to: Equality (process model) and inequality constraints (linear bounds of optimisation variables

There are therefore two optimisation problems, as represented mathematically below:

$$\underset{L, W, t_f}{\text{Min}} \quad T.E.C.1 \quad \text{and} \quad T.E.C.2$$
$$\underset{L, W, t_f}{\text{Max}} \quad Rej_{(Total)}$$

Subject to:

Equality constraints:

Process Model: $f(x, u, v) = 0$

Inequality constraints:

$$L^L \leq L \leq L^U$$
$$W^L \leq W \leq W^U$$
$$t_f^{\ L} \leq t_f \leq f^U$$

End-point constrain: $A = 7.845 \text{ m}^2$

6. Optimisation results

The optimisation results of the multi-stage RO process are given in Table 5, which shows the optimum values of membrane length (L), width (W), and feed channel height (t_f) for each stage and the optimised total energy consumptions of configurations A $(T.E.C.1)$ and B $(T.E.C.2)$ at the maximum chlorophenol rejection $Rej_{(Total)}$ and recovery rate $Rec_{(Total)}$ achieved. It is noteworthy to mention that the optimisation platform of gPROMS has given only one solution, instead of a set of non-dominant solutions as the case of Genetic Algorithm.[17]

Table 5. Optimal optimisation results of multi-stage RO process of with and without ERD at operating conditions of (initial conditions, 6.226E-3 kmol/m³, 5.166E-4 m³/s, 15 atm and 31 °C)

Firstly, it can be said that the total energy consumption can be reduced further when discarding the second objective function relating to maximising the chlorophenol rejection. However, the optimal results shown in Table 5 point to the possibility of having a higher rejection parameter at a lower energy consumption. In order to keep the highest water flux, the results also confirm the necessity to select specific membrane dimensions for stage 2 compared to similar specifications for stages 1 and 3. In other words, the alteration of stage 2 module dimensions was necessary for maximising the total recovery rate of this stage. This is the result of blending the two high concentration streams of stage 1, which induces the high feed flow rate stream of stage 2 (one pressure vessel). Therefore, the increase of the membrane width and the decrease of the membrane length play a significant role in reducing the feed flow rate along the whole section and yield a higher water flux and sustainable energy saving. Most importantly, the total energy consumption of configurations A and B exhibit a significant reduction of energy consumption - about 60.32 % from 2.034 kWh/m³ to 0.807 kWh/m³ and 54.42 % from 2.034 kWh/m³ to 0.927 kWh/m³ for configurations A and B respectively compared with the maximum performance of the individual membrane pilot-scale experiment of Sundaramoorthy *et al.* [13]. Essentially, the total recovery rate achieved in the proposed configurations is 53.55 % compared to only 22 % as per Sundaramoorthy's *et al.* [13] experiment. For convenience, the operating conditions at the maximum performance of Sundaramoorthy's *et al.* [13] experiment are given in Section 3. Having said the above, the total chlorophenol rejection achieved represents an increase of 12.6 % (from 83 % to 93.5 %) compared to the maximum rejection reported in the experiment of Sundaramoorthy *et al.* [13]. In the majority of cases, the capacity of the proposed configurations is comparable with the study of Al-Obaidi *et al.* [12], who achieved a maximum reduction of 19.2 % in total energy consumption of an individual spiral-wound RO module used to remove dimethylphenol from wastewater.

Table 5 shows that the optimum value of feed channel height is 0.5E-3 m. This is deemed reasonable in the case of removing chlorophenol because of the low possibility of fouling or scaling in the presence of low feed concentration (6.226-3 kmol/m³ equivalent to 800 ppm). This implies that a higher feed channel height value would be required in the optimisation problem when treating higher feed chlorophenol concentrations.

The results of this research have confirmed that the RO process can readily be used to achieve the stringent limits of high-toxic compounds concentration, which are set to increase in the future. The methodology presented in this research can also be easily implemented for complex wastewater of organic and non-organic compounds. However, the contribution of all compounds to the osmotic pressure must be assessed, and the extent to which the RO process presented in Fig. 1 can be successfully used to abate a complex wastewater must be explored. This is because chlorophenol has high hydrophilicity properties in water (easily dissolved in water).[18] Therefore, such complex wastewater rejection and energy consumption aspects of a multi-stage RO process need to be investigated in the future.

7. Conclusions

The impact of varying the membrane and module specifications on the overall energy consumption, chlorophenol rejection and total recovery rate has been investigated using two configurations of multi-stage RO process, with and without ERD for the removal of chlorophenol from wastewater.

Specifically, the research confirms the following key conclusions:

1. In a conventional RO plant, increasing the membrane width and decreasing the membrane length outside the manufacturer's specification and at the same time keeping a constant membrane area and module volume, yields a decrease in energy consumption but with a relatively small negative impact on chlorophenol rejection.
2. A noticeable increase of chlorophenol rejection, recovery rate, and decrease of energy consumption can be achieved by using a low feed channel height within a constant membrane area
3. A 50 % increase in the membrane area achieved by increasing the width at constant length is highly desirable as it yields a significant energy consumption reduction in the configurations tested, more so in B, despite a small reduction in chlorophenol rejection.
4. A 50 % increase in the membrane area achieved by concurrently increasing length and width at a constant module volume can lift the reduction of energy consumption despite the low reduction in chlorophenol rejection.
5. The multi-objective optimisation study identified the best module dimensions, which yield the lowest energy consumption and the highest chlorophenol rejection.
6. The multi-stage RO process can save more energy consumption in comparison to a single stage RO process because of the improvement made in the total recovery rate.

7. At least 60 % and 54 % energy consumption savings can be achieved with configurations A and B, with and without ERD, respectively in comparison with published data for an individual RO module (Sundaramoorthy *et al.*, [13]).

The above results are encouraging in that the performance of the RO system investigated can be enhanced further by implementing a high permeability membrane type, one that can save both energy and money and impact more definitely on the environmental. The next step of this research is to continue the investigation of both configurations with a higher chlorophenol concentration feed, with the expectation of a reduced energy cost per volume of produced permeate.

Nomenclature

A : Effective area of the membrane (m^2)

A_w : Solvent transport coefficient (m/atm s)

b : Feed and permeate channels friction parameter (atm s/m^4)

B_s : Solute transport coefficient (m/s)

C_b : The bulk feed solute concentrations at the feed channel (kmol/m^3)

C_f : The inlet feed solute concentrations at the feed channel (kmol/m^3)

$C_{f(plant)}$: The inlet chlorophenol concentration of the plant (kmol/m^3)

C_m : The dimensionless solute concentration in Eq. (1) in Table A.2 of Appendix A (dimensionless)

C_p : The permeate solute concentration at the permeate channel (kmol/m^3)

C_w : The solute concentration on the membrane surface at the feed channel (kmol/m^3)

D_b : The solute diffusion coefficient of feed at the feed channel (m^2/s)

D_p : The solute diffusion coefficient of feed at the permeate channel (m^2/s)

de_b : The equivalent diameters of the feed channel (m)

de_p : The equivalent diameters of the permeate channel (m)

J_s : The solute molar flux through the membrane (kmol/m^2 s)

J_w : The permeate flux (m/s)

k : The mass transfer coefficient at the feed channel (m/s)

L : The length of the membrane (m)

m_f : Parameter in Eqs. (7) and (8) in Table A.2 of Appendix A

$P_{f(in)}$: The inlet feed pressure (atm)

$P_{f(out)}$: The outlet feed pressure (atm)

$P_{f(plant)}$: Plant feed pressure (atm)

P_p : The permeate channel pressure (atm)

Q_b : The bulk feed flow rate at the feed channel (m^3/s)

Q_f : The inlet feed flow rate at the feed channel (m^3/s)

$Q_{f(plant)}$: Plant feed flow rate (m^3/s)

Q_p : The permeate flow rate at the permeate channel (m^3/s)

Q_r : The retentate flow rate at the feed channel (m^3/s)

R : The gas low constant (R = 0.082 atm m^3/ K kmol)

Re_b : The Reynold number at the feed channel (dimensionless)

Rec : Total permeate recovery (dimensionless)

$Rec_{(Total)}$: Total water recovery rate of the plant (dimensionless)

Rej : The solute rejection coefficient (dimensionless)

$Rej_{(Total)}$: Total chlorophenol rejection of the plant (dimensionless)

Re_p : The Reynold number at the permeate channel (dimensionless)

T : The feed temperature (°C)

$T_{(plant)}$: Plant feed temperature (°C)

$T.E.C.1$: Total energy consumption of the plant without ERD (kW h/m^3)

$T.E.C.2$: Total energy consumption of the plant with ERD (kW h/m^3)

t_f : Height of feed channel (m)

t_p : Height of permeate channel (m)

U_b : The bulk feed velocity at the feed channel (m/s)

W : The membrane width (m)

Subscript

μ_b : The Feed viscosity at the feed channel (kg/m s)

μ_p : The permeate viscosity at the permeate channel (kg/m s)

ρ_b : The feed density at the feed channel (kg/m^3)

ρ_p : The permeate density at the permeate channel (kg/m³)

ρ_w : Molal density of water (55.56 kmol/m³)

θ : Parameter in Eq. (11) in Table A.1 of Appendix A

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Fig. 1

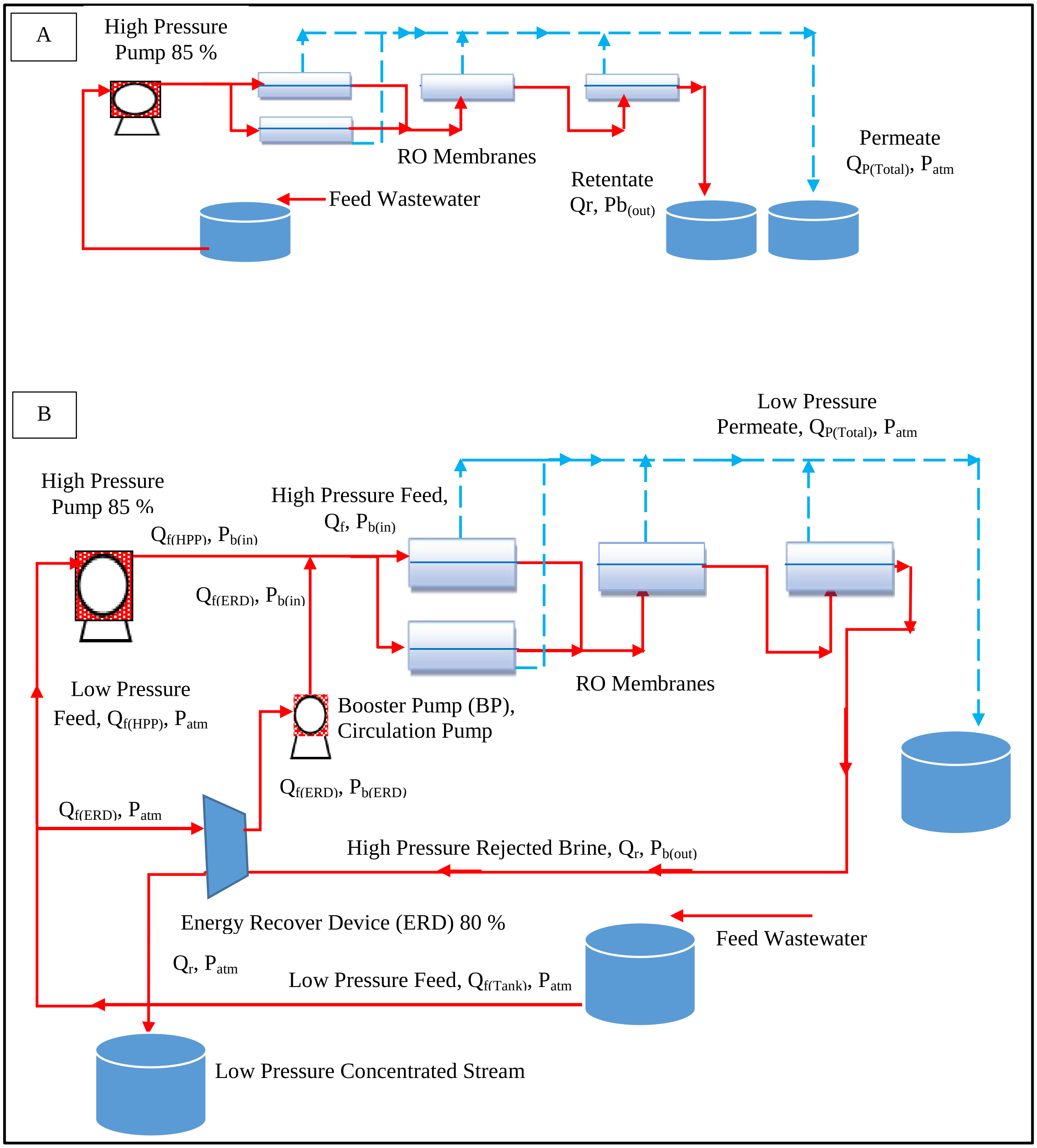
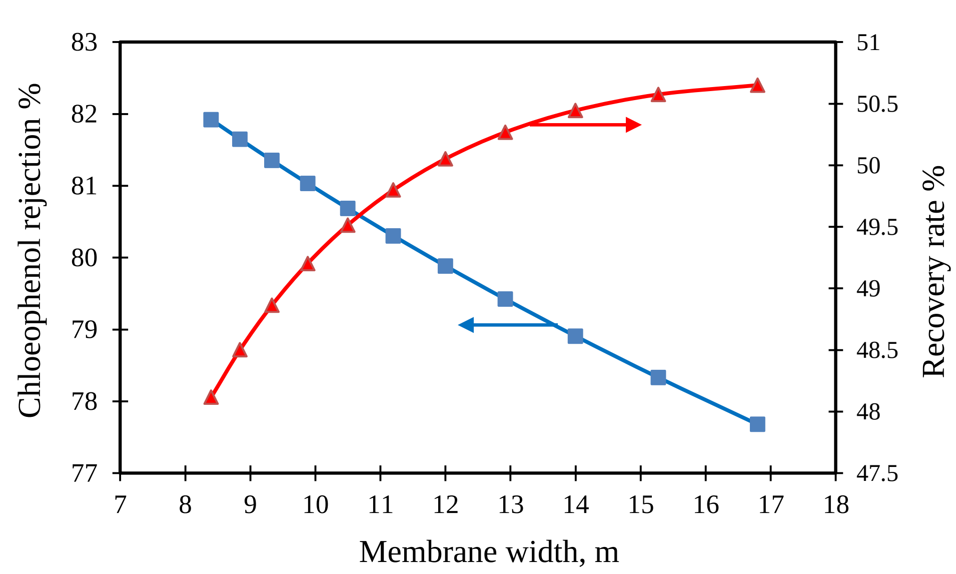

A
High Pressure Pump 85 %
RO Membranes
Feed Wastewater
Retentate
Qr, Pb(out)
Permeate
QP(Total), Patm
B
Low Pressure Permeate, QP(Total), Patm
High Pressure Pump 85 %
High Pressure Feed, Qf, Pb(in)
Qf(HPP), Pb(in)
Qf(ERD), Pb(in)
RO Membranes
Low Pressure Feed, Qf(HPP), Patm
Booster Pump (BP), Circulation Pump
Qf(ERD), Pb(ERD)
Qf(ERD), Patm
High Pressure Rejected Brine, Qr, Pb(out)
Energy Recover Device (ERD) 80 %
Feed Wastewater
Qr, Patm
Low Pressure Feed, Qf(Tank), Patm
Low Pressure Concentrated Stream

Fig. 2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48
47.5
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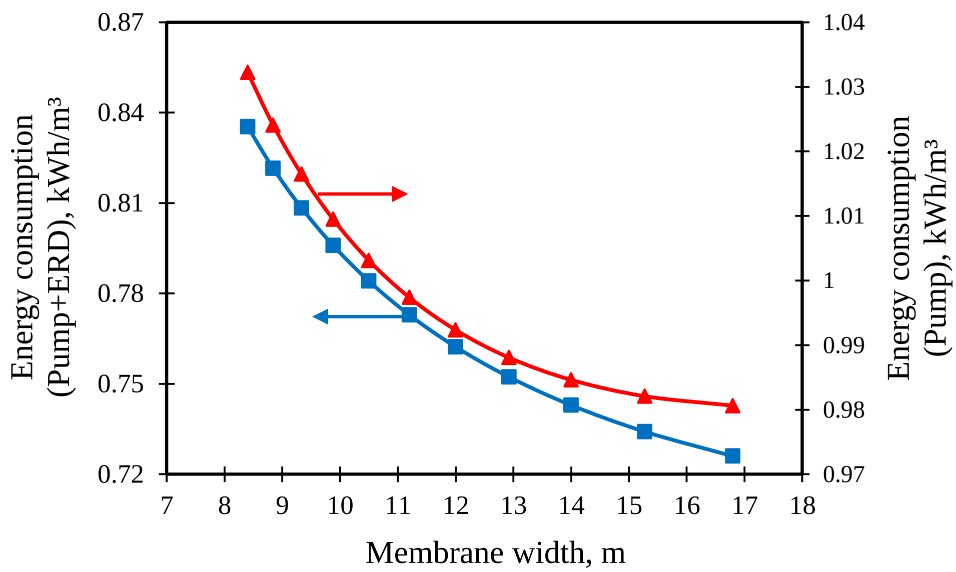
17
18
Chloeophenol rejection %
Recovery rate %
Membrane width, m

Fig. 3.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1.02
1.01
1
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0.98
0.97
7
8
9
10
11
12
13
14
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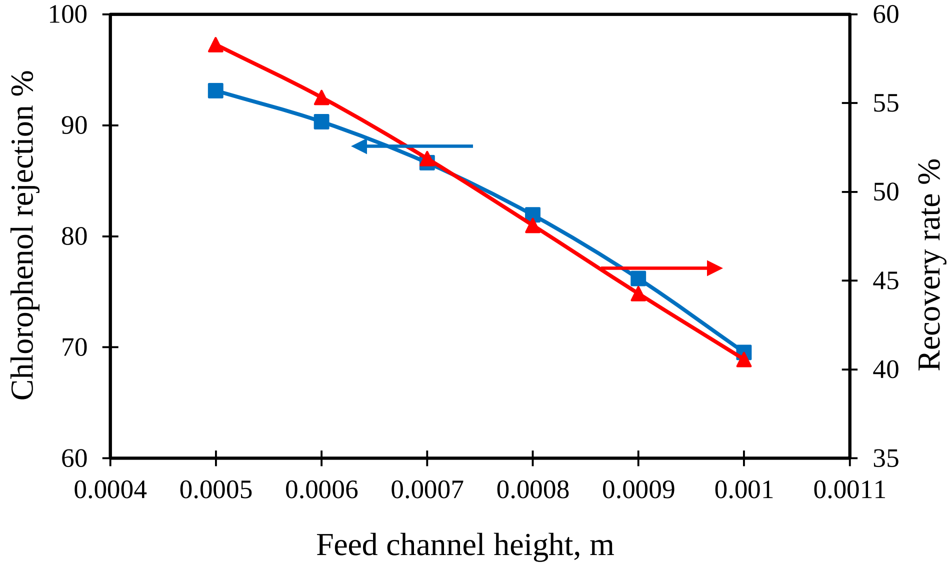
16
17
18
Energy consumption
(Pump+ERD), kWh/m³
Energy consumption
(Pump), kWh/m³
Membrane width, m

Fig. 4.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60
55
50
45
40
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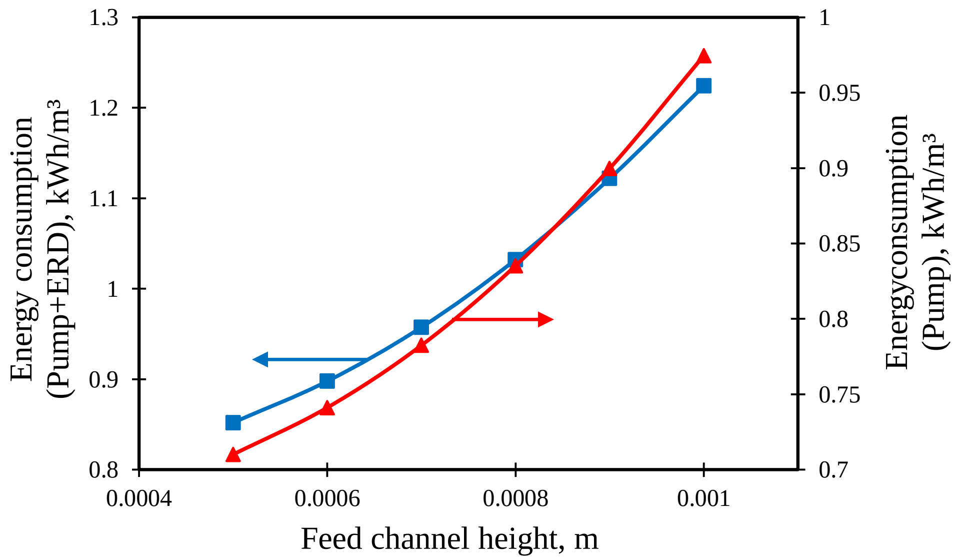
0.0005
0.0006
0.0007
0.0008
0.0009
0.001
0.0011
Chlorophenol rejection %
Recovery rate %
Feed channel height, m

Fig. 5.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1
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0.0006
0.0008
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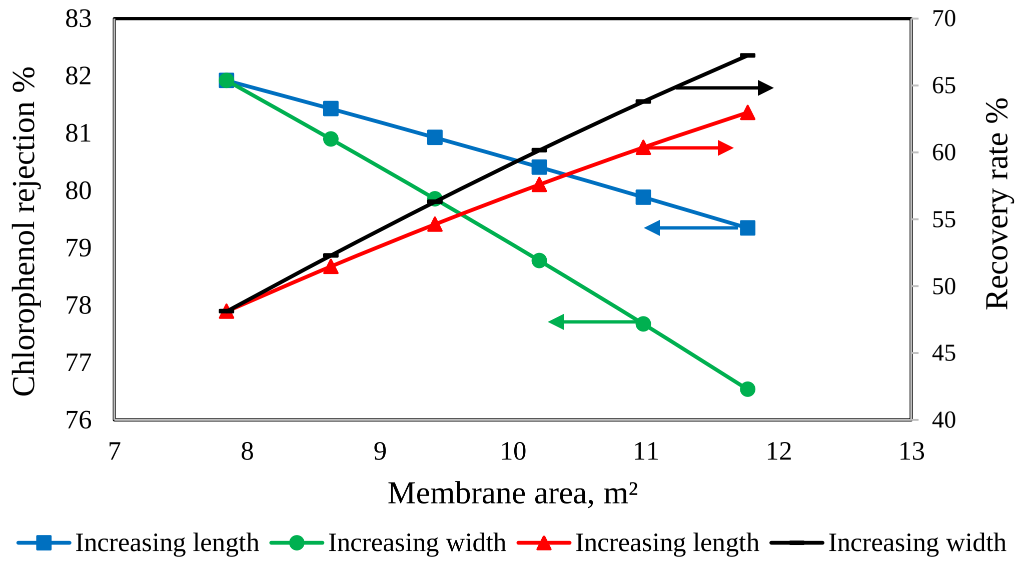
Energy consumption
(Pump+ERD), kWh/m3
Energyconsumption
(Pump), kWh/m3
Feed channel height, m

Fig. 6.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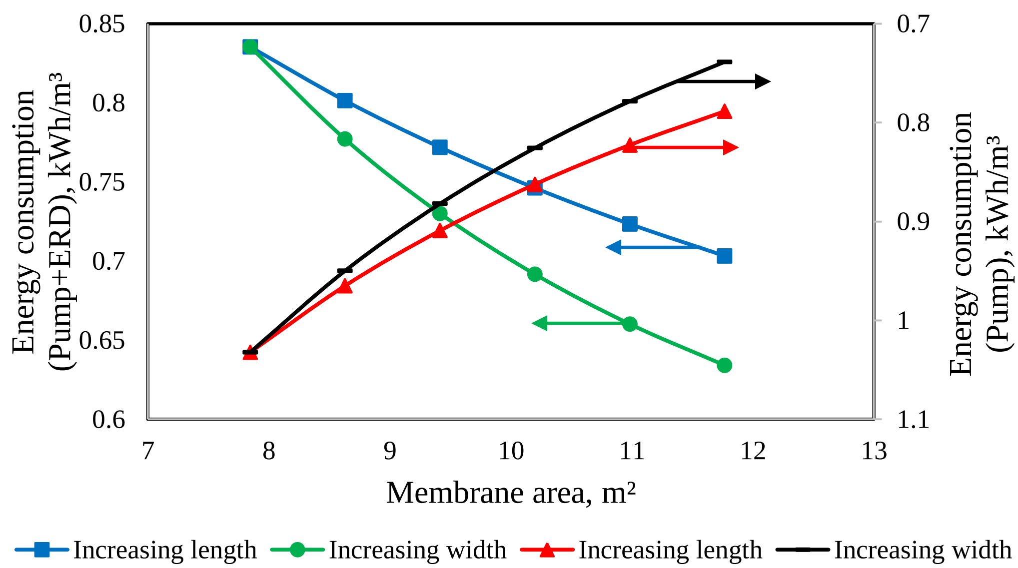
Chlorophenol rejection %
Recovery rate %
Membrane area, m²
Increasing length
Increasing width
Increasing length
Increasing width

Fig .7.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0.8
0.9
1
1.1
7
8
9
10
11
12
13
Energy consumption (Pump+ERD), kWh/m³
Energy consumption (Pump), kWh/m³
Membrane area, m²
Increasing length
Increasing width
Increasing length
Increasing width

Fig. 8.

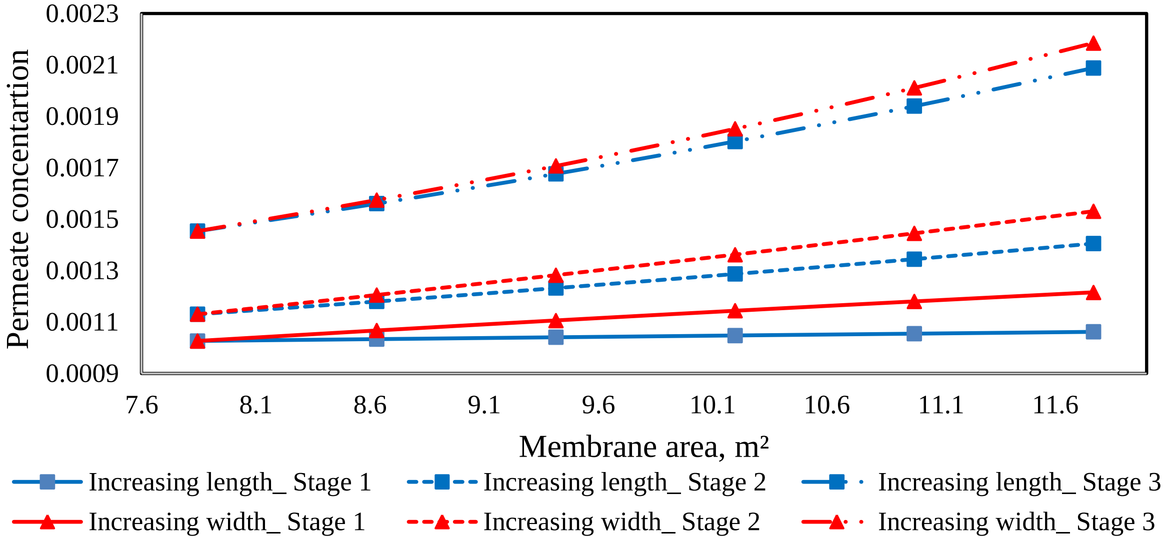

Fig. 9.

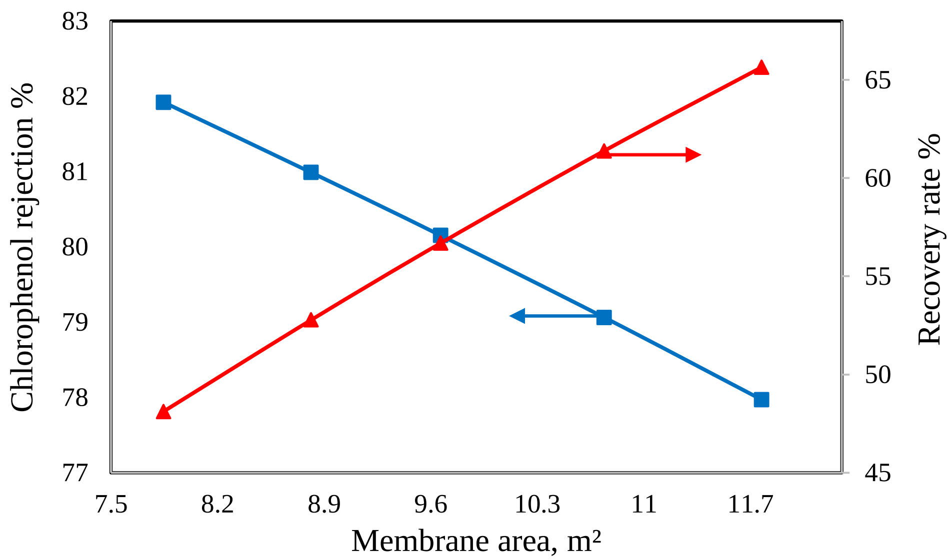

Fig. 10.

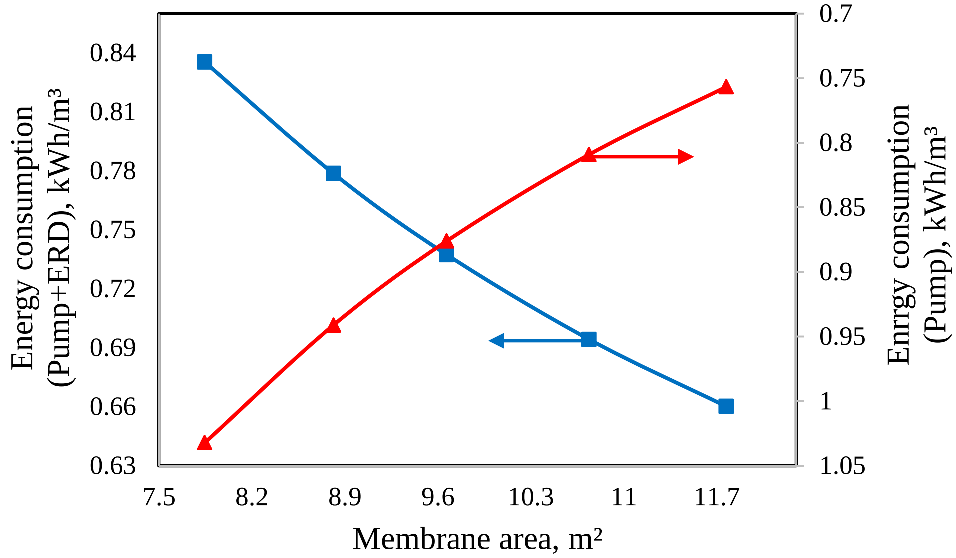

Table 1.

Parameter	Value
Membrane material and configuration	TFC aromatic polyamide composite, spiral wound
Model	HM4040-LPE
Feed spacer thickness (t_f)	0.8E-3 m
Permeate channel thickness (t_p)	0.5E-3 m
Number of turns	30
Module length (L)	0.934 m
Module width (W)	8.4 m
Membrane area (A)	7.845 m²
Membrane volume	6.2764E-3 m³

* The manufacturer

Table 2.

Parameter	Units	Value
A_w	m/atm s	9.5188E-7
B_s	m/s	8.468E-8
b	atm s/m^4	8529.45

Table 3.

Simulation set	Total energy consumption, kWh/m³		Chlorophenol rejection% $Rej_{(Total)}$	Total water recovery% $Rec_{(Total)}$
	$T.E.C.1$ (Pump)	$T.E.C.2$ (Pump+ERD)		
1	1.165	0.979	77.039	31.256
2	0.922	0.746	80.803	53.834
3	1.127	0.919	80.281	39.902
4	0.946	0.775	84.632	52.466
Sundaramoorthy *et al.* [13]	2.034	---	83.000	22.000

Table 4.

Parameter	Upper limit, m	Lower limit, m
Membrane length	1.4	0.5
Membrane width	12.6	8.4
Feed channel height	0.001	0.0005

Table 5.

Stage no.	Optimised membrane dimensions, m			Optimised total energy consumption, kWh/m³		Optimised chlorophenol rejection % $Rej_{(Total)}$	Total water recovery % $Rec_{(Total)}$
	L	W	t_f	$T.E.C.1$ (Pump)	$T.E.C.2$ (Pump+ERD)		
1	1.4	5.603	0.5E-3	0.927	0.807	93.5	53.555
2	1.092	7.184	0.5E-3				
3	1.4	5.603	0.5E-3				

Appendix A

Table A.1. Mathematical modelling of an individual spiral-wound RO system (Al-Obaidi *et al.*, [12])

Model Equations	Specifications	Eq. no.
$J_w = A_w \left[\left(\frac{\left(P_{f(in)} + P_{f(out)}\right)}{2} - P_p \right) - \left(R\ (T + 273.15)\ \left(C_w - C_p\right) \right) \right]$	The permeate flux (m/s)	1
$J_s = B_s\left(C_w - C_p\right)$	The solute flux (kmol/m² s)	2
$\frac{(C_w - C_p)}{(C_b - C_p)} = exp\left(\frac{J_w}{k}\right)$	The wall solute concentration (kmol/m³)	3
$U_b = \frac{Q_b}{W\ t_f}$	The bulk feed velocity (m/s)	4
$Q_b = \frac{Q_f + Q_r}{2}$	The bulk feed flow rate (m³/s)	5
$C_b = \frac{C_f + C_r}{2}$	The bulk concentration (kmol/m³)	6
$C_p = \frac{J_s}{J_w + J_s}$	The permeate solute concentration (kmol/m³)	7
$Q_f = Q_r + Q_p$	The retentate flow rate (m³/s)	8
$Q_f\ C_f = Q_r\ C_r + Q_p\ C_p$	The retentate concentration (kmol/m³)	9
$Q_p = J_w\ A$	The total permeated flow rate (m³/s)	10
$P_{b(out)} = \Big\{ P_{b(in)} - (b\ L\ Q_f) + \left(b\ W\ \theta\ \left(\frac{L^2}{2}\right)\left(\Delta P_{b(out)}\right)\right) - \left[b^2\ W\ \theta\ \left(\frac{L^3}{6}\right) Q_f \right] - \left[b^2\ W\ \theta\ \left(\frac{W\ \theta}{b}\right)^{0.5} \left(\frac{L^3}{6}\right) \left(\Delta P_{b(out)} - \Delta P_{b(in)}\right)\right] \Big\}$	The retentate pressure.[17]	11
$\theta = \frac{A_w\ B_s}{B_s + R\ (T + 273.15)\ A_w\ C_p}$	Parameter in Eq. (11)	12
$\Delta P_{b(in)} = P_{b(in)} - P_p$	The pressure difference at the inlet edge (atm)	13
$\Delta P_{b(out)} = P_{b(out)} - P_p$	The pressure difference at the outlet edge (atm)	14
$Rec = \frac{Q_p}{Q_f}\ x100$	The total permeate recovery (dimensionless)	15
$Rej = \frac{C_f - C_p}{C_f} x100$	The solute rejection (dimensionless)	16
$T.E.C.1 = \frac{\frac{\left(\left(P_{b(in)}\ x101325\right) Q_f\right)}{Q_{p(Total)}\ \varepsilon_{pump}}}{36E5}$	The specific consumption energy of HPP (kWh/m³) without ERD	17
$T.E.C.2 = \frac{\frac{\left(P_{b(in)}\ x101325\right) Q_{f(HPP)}\ \right) + \left(P_{b(in)}\ x101325\right) Q_{f(BP)}\ \right)}{Q_{p(Total)}\ \varepsilon_{pump}} - \frac{\left(P_{b(out)}\ x101325\right) Q_r\ \varepsilon_{ERD}}{Q_{p(Total)}}}{36E5}$	The specific consumption energy of HPP (kWh/m³) with ERD	18
$Q_{f(BP)} = Q_r$	Calculates the feed flow rate of Booster pump	19
$\varepsilon_{ERD} = \frac{P_{b(ERD)}}{P_{b(out)}}$	Calculates the pressure of ERD	20

Table A.2. Thermophysical properties of chlorophenol

Model Equations	Specifications	Eq. no.
$k = \frac{147.4\, D_b\, Re_b^{0.13}\, Re_p^{0.739}\, C_m^{0.135}}{2\, t_f}$	The mass transfer coefficient (m/s).[13]	1
$C_m = \frac{C_b}{\rho_w}$	The dimensionless solute concentration (dimensionless)	2
$D_b = 6.725E-6\ exp\left\{0.1546E-(3\ C_f\ x18.0125)\ -\frac{2513}{(T+273.15)}\right\}$	The diffusivity parameter at the feed channel (m²/s).[19]	3
$D_p = 6.725E-6\ exp\left\{0.1546E-(3\ C_p\ x18.0125)\ -\frac{2513}{(T+273.15)}\right\}$	The diffusivity parameter at the permeate channel (m²/s)	4
$\mu_b = 1.234E-6\ exp\left\{0.0212E-(3\ C_f\ x18.0153)+\frac{1965}{(T+273.15)}\right\}$	The dynamic viscosity (kg/m s) at the feed channel	5
$\mu_p = 1.234E-6\ exp\left\{0.0212E-(3\ C_p\ x18.0153)+\frac{1965}{(T+273.15)}\right\}$	The dynamic viscosity (kg/m s) at the permeate channel	6
$\rho_b = 498.4\ m_f + \sqrt{[248400\ m_f^2 + 752.4\ m_f\ C_f\ x18.01253]}$	The feed density (kg/m³)	7
$\rho_p = 498.4\ m_f + \sqrt{[248400\ m_f^2 + 752.4\ m_f\ C_p\ x18.01253]}$	The permeate density (kg/m³)	8
$m_f = 1.0069 - 2.757E-4\ (T)$	Parameter in Eqs. (7) and (8)	9
$Re_b = \frac{\rho_b\ de_b\ Q_b}{t_f\ W\ \mu_b}$	The Reynolds number at the feed channel (dimensionless)	10
$Re_p = \frac{\rho_p\ de_p\ J_w}{\mu_p}$	The Reynolds number at the permeate channel (dimensionless)	11
$de_b = 2t_f \qquad de_p = 2t_p$	The equivalent diameters of the feed and permeate channels (m)	12

Table A.3. Model validation results at several operating conditions

No	$P_{b(in)}$	T	C_f	Q_f	$P_{b(out)}$ (atm)	%Err	Q_r x10^4 (m³/s)	%Err	C_p x10^3 (kmol/m³)	%Error	Rej	%Err

	(atm)	(°C)	x10³ (kmol/ m³)	x10⁴ (m³/s)	Exp.	The.		Exp.	The.		Exp.	The.		Exp.	The.	
1	9.71	30	0.778	2.166	8.3	8.16	1.6	1.59	1.63	-2.2	0.366	0.345	5.5	61.4	62.48	-1.7
2	11.64	30	0.778	2.166	10.08	10.14	-0.6	1.5	1.50	0.3	0.363	0.362	0.2	63.8	62.45	2.1
3	13.58	30	0.778	2.166	12.04	12.14	-0.8	1.37	1.37	0.3	0.36	0.381	-6.0	66.2	62.21	6.0
4	7.77	31	6.226	2.166	6.24	6.145	1.5	1.828	1.84	-0.8	1.657	1.353	18.3	76.7	80.87	-5.4
5	9.71	31	6.226	2.166	8.11	8.129	-0.2	1.75	1.73	0.9	1.491	1.301	12.6	79.8	82.54	-3.4
6	11.64	31	6.226	2.166	9.98	10.10	-1.2	1.641	1.62	0.9	1.475	1.289	12.5	81	83.62	-3.2
7	13.58	31	6.226	2.166	11.85	12.08	-1.9	1.575	1.52	3.5	1.457	1.299	10.7	81.9	84.38	-3.0
8	5.83	30	0.778	2.33	4.46	4.043	9.3	1.957	2.06	-5.2	0.375	0.321	14.2	56.2	61.59	-9.5
9	7.77	30	0.778	2.33	6.35	6.038	4.9	1.86	1.93	-3.5	0.373	0.324	13.0	58.1	62.86	-8.2
10	9.71	30	0.778	2.33	8.22	8.031	2.2	1.742	1.79	-2.8	0.372	0.334	10.0	60.3	63.26	-4.9
11	11.64	30	0.778	2.33	10.09	10.01	0.7	1.639	1.66	-1.3	0.37	0.349	5.6	62.4	63.26	-1.3
12	13.58	30	0.778	2.33	11.96	12.00	-0.3	1.542	1.53	0.7	0.367	0.367	0.0	64.5	63.05	2.2
13	5.83	31	6.226	2.33	4.27	4.027	5.6	2.082	2.12	-1.9	1.726	1.46	15.2	74.5	78.15	-4.9
14	7.77	31	2.455	2.33	6.16	6.011	2.4	1.987	2.01	-1.1	1.645	1.321	19.6	76.6	81.15	-5.9
15	9.71	31	2.455	2.33	8.03	7.996	0.4	1.902	1.90	0.2	1.472	1.263	14.1	79.8	82.83	-3.8
16	11.64	31	2.455	2.33	9.9	9.970	-0.7	1.815	1.79	1.5	1.433	1.244	13.1	81.2	83.91	-3.3
17	13.58	31	2.455	2.33	11.77	11.95	-1.5	1.734	1.68	3.1	1.419	1.248	12.0	82.2	84.68	-3.0
18	7.77	31	1.556	2.583	6.17	5.825	5.5	2.148	2.20	-2.3	0.572	0.46	19.5	67.5	73.65	-9.1
19	9.71	31	1.556	2.583	7.79	7.817	-0.3	2.042	2.07	-1.3	0.553	0.46	16.8	69.7	74.83	-7.3
20	11.64	31	1.556	2.583	9.92	9.799	1.2	1.947	1.94	0.2	0.55	0.469	14.7	71.2	75.51	-6.0
21	13.58	31	1.556	2.583	11.79	11.79	-0.0	1.85	1.81	1.9	0.549	0.484	11.8	72.5	75.93	-4.7
22	9.71	31	2.335	2.583	8.03	7.811	2.7	2.08	2.09	-0.3	0.744	0.606	18.5	72.8	77.91	-7.0
23	11.64	31	2.335	2.583	9.84	9.791	0.4	1.97	1.96	0.3	0.733	0.612	16.5	74.2	78.75	-6.1
24	13.58	31	2.335	2.583	11.74	11.78	-0.3	1.868	1.84	1.4	0.726	0.626	13.8	75.7	79.30	-4.7
25	7.77	31	6.226	2.583	6.03	5.805	3.7	2.253	2.26	-0.5	1.549	1.278	17.4	77.8	81.52	-4.7
26	9.71	31	6.226	2.583	7.9	7.790	1.3	2.17	2.15	0.8	1.486	1.212	18.4	79.4	83.23	-4.8
27	11.64	31	6.226	2.583	9.75	9.765	-0.1	2.09	2.04	2.4	1.387	1.186	14.4	81.5	84.33	-3.4
28	13.58	31	6.226	2.583	11.65	11.74	-0.8	2.012	1.93	4.1	1.325	1.182	10.7	83	85.10	-2.5