Design of reverse osmosis filtration system for the supply of clean water from saltwater wells in Tanjung Lame village

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Abstract. Groundwater sources from community wells in Tanjung Lame village, Pandeglang regency, are not suitable for consumption, due to high salinity. In addition, reverse osmosis (RO) filtration system is a typical and efficient alternative technology adopted during the processing of clean water from saltwater sources. However, large amount of pressure is usually involved for a conventional single-stage RO. The purpose of this study, therefore, was to design a multi-stage RO filtration system capable of operating at low pressures. Therefore, the adopted model with a configuration of hybrid RO/NF permeate staging has proven to produce potable water from saltwater wells in Tanjung Lame village at low pressures. Moreover, the system was operated at the first and second stage RO/NF pressure of 6 and 3 bar, respectively. Under these circumstances, salt rejection and permeate TDS were estimated at 97.02% and 86 ppm, respectively in order to obtain optimum outcome. Furthermore, the product water recovery rate was evaluated at 37%, and a permeate flow rate of 1.85 liters/minute. The systems’ specific energy consumption (SEC) was estimated to be 1.802 kWh/m³, while a reduced value of 58.39% was observed for conventional single-stage RO.

Keywords: Clean water; RO filtration system; Pressure; Water recovery rate; Salt rejection

1. Introduction

Easier access to clean water is one major provision of the sustainable development goals (SDGs) by the United Nations (UN). The need for potable water increases significantly every year, but with decreasing availability, particularly during dry season. In addition, the World Health Organization (WHO) reports in 2015 showed 9% of the world’s population lack access to safe drinking water, while the demand continues to rise due to increasing population [1]. In Tanjung Lame village, Pandeglang regency, groundwater sources contain high salt concentration, and therefore, are not fit for consumption. This is hardly surprising as some coastal areas in Indonesia also show available salty groundwater. An effective method for processing clean water from saltwater is the application of reverse osmosis (RO) filtration system.

This mechanism is an alternative water treatment using a semi-permeable membrane to remove impurities, including ions, molecules, and large particles. The treatment systems are less complicated and easier to operate compared to evaporation and ion exchange methods, hence are convenient for rural applications. However, the pressure needed for a conventional single-stage RO system is very

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high with potentials to cause high electric energy utilization e.g. pumps [2]. For seawater desalination, the required pump pressure extends above 40 bar, while the water recovery rate ranges between 40-50%. Therefore, the specific energy consumption (SEC) to produce clean water from seawater is relatively high. The theoretical SEC required by a conventional single-stage RO is 3.086 kWh/m$^3$, and this produces drinking water by reducing the total dissolved solids (TDS) from 35,000 to 350 ppm [3].

Based on literatures, several modifications on the RO filtration system to lower the pressure have been developed, including two-stage mechanism configured for concentrate staging. In this operation, concentrate stream is reprocessed, and is then combined with the permeate from the first stage. This successively decreases the pressure, although the TDS remained relatively high. Moreover, the fouling rate of the second stage RO expands as the membrane recycles the concentrate [4]. The purpose of this research, therefore, is to design permeate staging configuration, where the permeate stream in the first stage acts as feed in the second stage. This condition tends to reduce the pressure and the TDS. Furthermore, hybrid RO/NF membranes are employed in every stage in an effort to increase water recovery rate.

2. Materials and methods

2.1. Feedwater and membrane modules

This experiment collects water from saltwater wells in Tanjung Lame village, into the feed tank maintained at constant TDS. The feed with permeate staging configuration shows a TDS value of 2,490 ppm, while with hybrid RO/NF, the value obtained at 2,890 ppm. However, all membrane modules used are of ultra-low-pressure, particularly RO TCF membrane-type ULP-3013-400 for the first stage RO membrane, RO membrane-type WW-2012-100 for the second stage RO membrane, Kusatsu NF membrane-type NF-2812-500 for the first stage NF membrane, and NF-1812-150 for the second stage NF membrane. Therefore, the membranes applied for the first and second stage are 3 and 6, respectively.

2.2. Experimental installation and procedure

Two-stage permeate staging RO filtration system was applied, and Figure 1 represents a schematic diagram of the experimental settings. In this configuration, 3 UF membranes with cross-flow-type were employed as pretreatment. Permeate stream from the UF membrane flows to the first stage setup, and is connected to a low-pressure switch to control the first stage pump. This switch is turned off at very low feedwater pressure (less than 1.5 bar) in order to prevent pump damage. However, the first stage comprising 3 pumps, propels water known to contain 3 RO membranes, where the streams from the first membrane flow to the second stage pump. This stream further connects to a low-pressure switch used to control the second stage pump, and is turned off when the permeate flow pressure from the first RO membrane appears very insignificant (less than 1.5 bar). Furthermore, the second stage comprising three pumps, pushes water to the second stage RO, known to consist of 6 membranes. Rejection stream from each RO membrane links to the valve and pressure gauge to control the membrane pressure. The permeate stream from each stage RO is channeled to the rotameter to measure the volumetric flow rate. Subsequently, the permeate stream from the second RO membrane is collected in the clean water tank. In the configuration of permeate staging, the variations of transmembrane pressure used in the first and second stage RO are 3, 4, 5, 6, 7 bar and 2, 3, 4, 4.5 bar, respectively, while for hybrid RO/NF configuration, the change in values are 5, 6, 7 bar and 3, 4 bar, correspondingly. The feed flow rate is set constant at 5 liters/minute.
3. Result and discussion

3.1. Configuration of permeate staging
The first configuration is the permeate staging, where the applied modules were RO membranes. Filtration system performance was evaluated by the effect of transmembrane pressure on salt rejection and water recovery rate.

3.1.1. Effect of transmembrane pressure on salt rejection. Salt rejection is a very important parameter used to determine the RO performance. In addition, the salt rejection (in %) is described as the ratio between salt concentrations that can be rejected into the rejection streams and salt concentrations in the feed streams. Figure 2 and Table 1 show the effects of transmembrane pressure on the salt rejection in the configuration of permeate staging.

![Figure 2](image-url)
permeate staging.

Table 1. Effect of transmembrane pressure on the salt rejection in the configuration of permeate staging.

| Pressure (bar) | Salt rejection (%) | TDS of clean water (ppm) | Volumetric flow rate of clean water (liters/minute) |
|---------------|--------------------|--------------------------|-----------------------------------------------|
| First stage RO | Second stage RO    | First stage RO | Second stage RO | Final value |                |                      |
| 3             | 2                  | 92.81                 | 81.01                 | 98.63        | 34              | 0.54                |
| 4             | 2                  | 93.25                 | 83.93                 | 98.92        | 27              | 0.60                |
| 4             | 3                  | 93.33                 | 75.90                 | 98.39        | 40              | 0.87                |
| 5             | 2                  | 93.86                 | 84.31                 | 99.04        | 24              | 0.51                |
| 5             | 3                  | 93.90                 | 82.89                 | 98.96        | 26              | 0.96                |
| 6             | 2                  | 94.02                 | 84.56                 | 99.08        | 23              | 0.57                |
| 6             | 3                  | 94.14                 | 84.93                 | 99.12        | 22              | 0.96                |
| 6             | 4                  | 94.14                 | 71.92                 | 98.35        | 41              | 1.05                |
| 7             | 2                  | 94.14                 | 72.60                 | 98.39        | 40              | 0.66                |
| 7             | 3                  | 94.14                 | 76.71                 | 98.63        | 34              | 0.96                |
| 7             | 4                  | 94.22                 | 76.39                 | 98.63        | 34              | 1.20                |
| 7             | 4.5                | 94.22                 | 58.33                 | 97.59        | 60              | 1.32                |

The results, as shown in Figure 2 and Table 1, indicate the salt rejection tend to increase as transmembrane pressure gradually rises. Subsequently, as the pressure continues to enlarge, the salt rejection actually observes a decline. Increased transmembrane pressure also improves the salt rejection, although a linear curve is not obtained [5]. Transmembrane pressure known to exceed osmotic pressure instigates the water molecules to diffuse from the saline solution in the feed stream to the permeate stream through the semi-permeable layer. This tend to also enhance the diffusion rate of water molecules to enable the salt rejection increase as the rejection stream become more concentrated, and also creates a concentration polarization between the two sides of the semi-permeable layer. High polarization concentration causes the efficiency of salt separation to decrease, therefore resulting to a maximum extracted salt concentration from the rejection stream [6].

The RO membranes are imperfect barriers to dissolved salt in feedwater, hence salt is always needed to diffuse with water molecules through a semi-permeable membrane referred to as salt passage. As the transmembrane pressure continues to increase beyond its optimum pressure, the salt flow is forced to diffuse through the membrane with a diffusion rate exceeding the salt flow rate in the rejection stream. This enables more salt to diffuse towards the permeate flow [5], as the passage increases in respect to decreasing salt rejection.

Transmembrane pressure exceeding the mechanical strength of the semi-permeable membrane also triggers mechanical damage to the membrane. Therefore, the semi-permeable membrane is not a good separator for salt and water solution [7]. This also increases the salt concentration permeating the membrane and further lowers the salt rejection level. To obtain optimum results, the designed RO filtration system is operated at the first and second stage of RO pressure at 6 and 3 bar, respectively. Under these circumstances, the salt rejection is evaluated at 99.12% with permeate TDS of 22 ppm. The designed RO filtration systems with the configuration of permeate staging has proven an effective performance in salt rejection.

3.1.2. Effect of transmembrane pressure on water recovery rate. Another parameter employed to show the performance of the designed RO filtration system is the water recovery rate (in %). This is known as the ratio between the permeate and feed flow rates. Higher salt rejection and water recovery instigate enhanced performance. Figure 3 and Table 2 show the effects of transmembrane pressure on water recovery rate.
Figure 3 shows the results of water recovery rate is directly linked to transmembrane pressure. This is due to an increase in transmembrane pressure, and further instigates the rise in diffusion flux in the RO membrane [5]. The maximum water recovery rate is achieved at the first and second stage with RO pressure of 7 and 4.5 bar, respectively, with an estimation of 26.4%. At the optimum pressure that produces the maximum salt rejection, the water recovery rate achieved is only 19.2%, with the flow rate of clean water at 0.96 liters/minute.

Based on the experimental study, the optimum condition for operating the machine is specified at 12 hours per day, with a 30 mins time lag after every 4 hours of operation. This is aimed at avoiding pump damage as a result of overheating. For instance, as the machine is operated for 12 hours per day, the total volume of product is achieved at 691.2 liters/day, although inadequate to meet the needs of 105 families in Tanjung Lame. Moreover, the average clean water consumption per family is 10 liters/day [8]. This shows the total potable water consumption at 1,050 liters/day. One method to increase the water recovery rate is the configuration of hybrid RO/NF permeate staging.
3.2. **Configuration of hybrid RO/NF permeate staging**

In this configuration, the first RO membrane of each stage is replaced by NF membrane. The design of RO filtration system with hybrid RO/NF consists of 2 RO membranes and 1 NF membrane on the first stage and 5 RO membranes and 1 NF membrane on the second.

3.2.1. **Effect of transmembrane pressure on salt rejection.** Figure 4 and Table 3 shows the effects of transmembrane pressure on the salt rejection in the configuration of hybrid RO/NF permeate staging.

![Figure 4](image-url)

**Figure 4.** Effect of transmembrane pressure on the salt rejection in the configuration of hybrid RO/NF permeate staging.

| Pressure (bar) | Salt rejection (%) | TDS of clean water (ppm) | Volumetric flow rate of clean water (l/min) |
|---------------|--------------------|--------------------------|-------------------------------------------|
| First stage RO | Second stage RO    | First stage RO           | Second stage RO                           | Final value |
| 5             | 3                  | 65.47                    | 92.08                                     | 97.27       |
| 6             | 3                  | 63.67                    | 91.81                                     | 97.02       |
| 6             | 4                  | 63.32                    | 83.40                                     | 93.91       |
| 7             | 3                  | 60.21                    | 85.65                                     | 94.29       |
| 7             | 4                  | 59.86                    | 77.24                                     | 90.87       |

| Pressure (bar) | Salt rejection (%) | TDS of clean water (ppm) | Volumetric flow rate of clean water (l/min) |
|---------------|--------------------|--------------------------|-------------------------------------------|
| RO/NF[1]: 5 bar |                   |                          |                                            |
| RO/NF[1]: 6 bar |                   |                          |                                            |
| RO/NF[1]: 7 bar |                   |                          |                                            |

Figure 4 and Table 3 show the salt rejection level declined as the transmembrane pressure increases. This is caused by pressure variations extending beyond the optimum desalination point. The existence of the NF membrane in hybrid RO/NF reduces the optimum transmembrane pressure compared to the optimum transmembrane pressure of the first configuration. This is due to lower operating pressure of the NF membrane compared to RO membrane [9].

There is a replacement of RO membrane in the second stage with an NF membrane. This causes slightly lower salt rejection compared to permeate staging. However, the decline in the final salt rejection is not very significant, particularly at low pressures. This also shows the NF membrane used in the second stage is preferred to separate salts compared to the NF membrane in the first. In addition, the level of monovalent salts separation extends to 70% [9], while the ability of NF membranes to decompose the salts varies based on pore size [10].
To obtain maximum salt rejection, the filtration system is operated at the first and second stage with pressure of 5 and 3 bar, respectively. Under these circumstances, the salt rejection appears at 97.27%, with the TDS of 79 ppm. The salt rejection and TDS are close to the optimum pressure results of the first and second stages specified at 6 and 3 bar, respectively. At these conditions, the salt rejection and TDS are obtained at 97.07% and 86 ppm, respectively. The designed RO filtration systems with the configuration of hybrid RO/NF permeate staging has proven a good performance in salt rejection.

3.2.2. Effect of transmembrane pressure on salt rejection. Figure 5 and Table 4 show the effects of transmembrane pressure on the water recovery rate in the configuration of permeate staging.

**Table 4. Effect of transmembrane pressure on the water recovery rate in the configuration of hybrid RO/NF permeate staging.**

| Pressure (bar) | Water recovery rate (%) | TDS of clean water (ppm) | Volumetric flow rate of clean water (liters/minute) |
|---------------|-------------------------|--------------------------|-----------------------------------------------|
| First stage RO | Second stage RO | First stage RO | Second stage RO | Final value |  |
| 5  | 3  | 59.00 | 42.37 | 25.00 | 79 | 1.25 |
| 6  | 3  | 68.00 | 54.41 | 37.00 | 86 | 1.85 |
| 6  | 4  | 79.00 | 67.09 | 53.00 | 176 | 2.65 |
| 7  | 3  | 89.00 | 52.81 | 47.00 | 165 | 2.35 |
| 7  | 4  | 90.00 | 75.56 | 68.00 | 264 | 3.40 |

Figure 5 and Table 4 indicate the water recovery rate is directly proportional to the transmembrane pressure. As the pressure increases, the permeate flux also increases until the salt concentration reaches its equilibrium [6]. The NF membrane inclusion enables a higher water recovery rate compared to permeate staging, and also shows an enhanced water flux than RO membrane due to the presence of negatively charged hydrophilic group [11].

In hybrid RO/NF permeate staging, the maximum water recovery rate, estimated at 68%, was obtained at the first and second stage RO/NF transmembrane pressures of 7 and 4 bar, respectively. Under these circumstances, the salt rejection appeared very low, but achieves 90.87% with clean water TDS of 264 ppm. At the pressure of maximum salt rejection, the water recovery rate acquired is 25%.
Also, at the first and second stage with pressures of 6 bar and 3 bar, the decrease of salt rejection is insignificant compared to its maximum value (less than 0.5%). However, the expected water recovery rate increased significantly. However, the salt rejection at that pressure only decreased by 0.25%, from 97.27 - 97.02%, while the water recovery increased by 12%, from 25 - 37%. Therefore, the optimum pressure selected in the configuration of hybrid RO/NF permeate staging are at the first and second stage of RO/NF transmembrane pressures of 6 and 3 bar, respectively.

At the specified optimum pressure, the water recovery rate achieved is 37%, with a flow rate of produced clean water at 1.85 liters/minute. For instance, as the machine is operated for 12 hours a day, the total flow rate becomes 1,332 liters/day. This volume is assumed to meet the needs of Tanjung Lame’s population.

3.2.3. Specific energy consumption (SEC). The energy efficiency of the RO filtration system is expressed in the form of specific energy consumption (SEC), and is defined as the energy needed to produce one unit/volume of clean water. In addition, the energy unit commonly used in desalination applications is kilo-watt-hour (kWh). To get the SEC value, the machine with the configuration of hybrid RO/NF permeate staging is operated for 1 hour at optimum pressure. However, the watt-meter records the amount of electrical energy consumed in 1 hour as 0.20 kWh and a steady flow rate of clean water product at 1.85 liters/minute. In addition, the volume of clean water produced in 1 hour is 0.111 m$^3$. Therefore, the SEC value of the designed RO filtration system in this study arrived at 1.802 kWh/m$^3$. The theoretical SEC required by conventional single-stage RO to produce drinking water by reducing the TDS value from 35,000 to 350 ppm at a pressure of 55.5 bar is estimated at 3,086 kWh/m$^3$ with a water recovery rate of 50% [9]. In addition, the SEC value of the designed RO/NF filtration system is reduced to 58.39% from the SEC of conventional single-stage RO. For this reason, the designed RO filtration system using the configuration of hybrid RO/NF permeate staging has been proved as a more successful performance compared to the conventional single-stage RO filtration system.

4. Summary
The design of RO filtration system with configuration of hybrid RO/NF permeate staging comprising 2 RO membranes and 1 NF membrane on the first stage and 5 RO membranes and 1 NF membrane on the second stage has proven to produce clean water from saltwater wells at low pressures. In addition, the volume generated is known to meet the total consumption of Tanjung Lame village, Pandeglang regency, Banten. To obtain optimum results, the configuration operates at the first and second stage RO/NF with pressures of 6 and 3 bar, respectively. Under these circumstances, the salt rejection and TDS are obtained at 97.02% and 86 ppm, respectively. However, the water recovery and permeate flow rates were estimated at 37% and 1.85 liters/minute, correspondingly. Specific energy consumption (SEC) of the designed RO filtration system is 1,802 kWh/m$^3$. Furthermore, the SEC value of the designed RO filtration system reduces to 58.39% from the conventional single-stage RO. The designed RO filtration systems with the configuration of hybrid RO/NF permeate staging has been proved as an effective performance compared to conventional single-stage RO filtration systems.

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