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# Effect of temperature on energy consumption and recovery rate of the reverse osmosis brackish systems in a different arrangement

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**Abstract.** One of the first water treatment technologies used by humans is Reverse Osmosis (RO). It has become a sustainable alternative solution to the problem of water scarcity in the current world conditions. In this research, the effects of temperature and pH on efficiency, energy consumption, and outlet water quality from simple single-stage RO systems, single-stage hybrid, simple two-stage, and two-stage hybrid are investigated using RO software. The results depict that at all temperatures, the two-stage RO system is more efficient in terms of efficiency, and the hybrid two-stage system has the best performance in terms of energy consumption. Moreover, the pH of the water entering the system has no effect on the efficiency and energy consumption of desalination plants. In terms of water quality, all the four desalination plants reduced the concentration of harmful ions to the desired level, but single-stage systems outperformed two-stage systems. In terms of corrosion index, two-stage systems outperformed single-stage systems. Furthermore, the corrosion rate of water could be significantly reduced by increasing the temperature and adding sodium hydroxide. In addition, the obtained results showed that the operating pressure on the RO system decreased as the temperature increased.



## 1. Introduction

Today, human need for fresh water is clear. Many people around the world encounter the challenge of fresh water. In many parts of the world, due to global warming and industrial development, especially in developing countries, they encounter water shortage or polluted water problems [1,2]. Meanwhile, the Middle East and central regions of the Iranian plateau are experiencing worse conditions than other regions due to drought and inadequate rainfall [3–5]. In recent years, due to inadequate rainfall, successive droughts, and uncontrolled rise of water consumption, the need for rational and long-term solutions to address the problem of fresh water shortage has been raised as a new concern and challenge [6,7]. Seawater and other saline waters do not meet direct human consumption requirements as well as agricultural and industrial purposes [8,9]. According to the World Health Organization (WHO) standards, the maximum allowable Total Dissolved

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Solids (TDSs) in water are about 500 ppm. However, these materials in saline water contain TDSs in the range of 10000 to 45000 ppm. Therefore, fresh water shortage in many areas is met by the desalination of saline water [10,11].

Nowadays, desalination of seawater and brackish water can be a useful process against the shortage of freshwater resources on a global scale [12,13]. Water desalination has become a life-saving technology, especially in the Middle East and Africa, where rainfall is insufficient [14,15]. According to technological advances and cost trends, the most popular commercial desalination processes include Multi-Effect Distillation (MED), Multi-Stage Flash distillation (MSF), Vapor Compression (VC), Reverse Osmosis (RO), and Electro Dialysis (ED) [16,17]. It has been found that almost the entire energy consumption of conventional desalination units comes from the combustion of fossil fuels [16–20]. Consumption of fossil fuels contributes to global warming and acid rain by emitting Greenhouse Gases (GHG) and other harmful emissions [21].

Other emerging low-consumption desalination technologies are still at the research and development phase and have not been scaled for commercialization. These technologies include Membrane Distillation (MD), Forward Osmosis (FO), Capacitive Deionization (CDI), Pressure Reverse Osmosis (PRO), and Adsorption Desalination (AD) [22–24]. According to the Global Water Intelligence (GWI) DesalData, a total of $93700 million will be spent on water desalination projects over the next four years [25]. Approximately $51600 million is allocated only for operating expenses. As illustrated in Figure 1, approximately 50% of operating costs have been spent on thermal and electrical energy [25,26].

The amount of energy required for the desalination process depends upon the quality of feed water, the level of water treatment, the treatment technology used by the center, and the capacity of the unit [27]. Table 1 shows different energies required to obtain one cubic meter of drinking water when purifying water from different sources. The dependence of water treatment

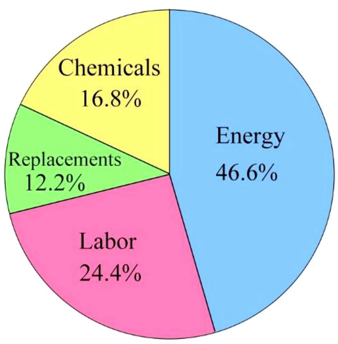


**Figure 1.** Operating costs for desalination plants [24].

**Table 1.** The required energy for one cubic meter of drinking water with different water sources [25,28].

| Source type | Energy consumption ($kWh/m^3$) |
|---|---|
| Surface water (rivers or lakes) | 0.37 |
| Groundwater | 0.48 |
| Purified wastewater | 0.62–0.87 |
| Recycled effluent water | 1.0–2.5 |
| Sea water | 2.58–8.5 |

on energy, as well as the significant amount of energy consumption for drinking water supply, is quite clear. In 2019, the amount of water treatment in newly established desalination units was almost twice as much as the units built in 2018 [25,28]. This continuously ascending trend in water treatment by desalination plants leads to increased energy consumption and costs. Therefore, the need for research and development to reduce energy consumption and achieve higher efficiency in industrial systems is essential [29].

In general, desalination technologies consist of thermal and membrane separation processes. Both thermal and membrane-based processes are essential for fresh water supply; thus, reducing their energy demand through research advances is significant for both [30]. Thermal desalination technologies require higher energy and costs maintenance, which make them less attractive [31]. In some parts of the world, such as the Persian Gulf, the use of thermal desalination plants is still expected due to high access to oil for energy supply. However, interest in RO-based desalination has increased in recent years in the Persian Gulf region due to significant technological advances [32,33]. One of the most economical industrial methods of water desalination is the RO system; according to Figure 2, approximately 69% of water desalination is fulfilled in this way [34]. In the RO systems, high-pressure pumps are commonly used, leading to high energy

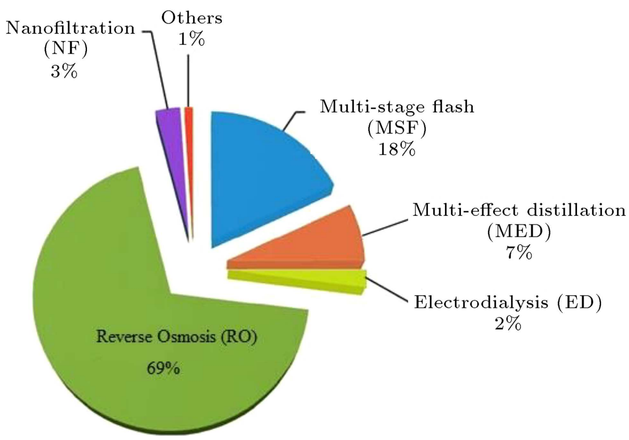


**Figure 2.** Distribution of desalination methods all over the world [33].

consumption. Hence, achieving an optimal amount of energy in such systems is essential. It is worth noting that in marine systems, the amount of energy consumption is much higher [35]. Due to the difficulties in high recovery processes for single-stage RO systems, the hybrid and multi-stage systems have recently been proposed as suitable designs for the RO process [36,37].

Agashichev and Lootahb investigated the impact of temperature parameters and several hydrodynamic parameters on the efficiency of treated water and energy consumption in RO systems. The results represented that increasing temperature promoted efficiency and reduced energy consumption [38]. Goosen et al. investigated the effect of temperature on water treatment in polymer membranes. Their results demonstrated that polymer membranes were susceptible to temperature changes. In addition, by increasing temperature from 20°C to 40°C, the rate of purified water flux increased to 60% [39]. Jin et al. experimentally and theoretically modeled the effect of 15, 25, and 35°C temperatures on the rate of filtered water, yield, mass transfer, and sediment level in both types of brackish membranes. Their results depicted that increasing the temperature would increase the amount of treated water and reduce energy consumption [40]. Molina et al. tested two low-energy and high-efficiency marine membranes from Dow, FILMTEC, designed with ISD in four different geographical areas. They found that ISD systems caused less energy consumption, higher flux, and greater efficiency. They also illustrated that these designs resulted in dimensional optimization of the RO system, pre-treatment system, and inlet feed pressure [41].

Mustaqimah et al. reported single- and two-stage RO system modeling and found that by increasing feed pressure, the TDS of the product water would increase, as well. The amount of water produced and recovered by the two-stage TDS was more considerable than that by the single-stage counterpart [42]. Peñate and García-Rodríguez reported a hybrid membrane design in the entering stage, which was a new method for the RO system. The results depicted that HID (Hybrid Inter Design) could increase the capacity of the RO system plants [43].

Kim and Hong designed a new single-stage split partial single-pass structure. They mixed the output water from the downstream membranes in the Pressure Vessel (PV) with the input feed water. They showed that the highest energy efficiency could be achieved when the water leaving the last membranes returned and be mixed with the feed water. They also depicted that this design had 15% better water quality than conventional single-pass RO systems with uniform flux distribution, less sedimentation rate, and high operating conditions concerning the marine RO system [44]. Kim and Hong used a hybrid marine RO system to improve water quality and energy efficiency. They designed various hybrids with three different types of commercial membranes to achieve a cost-effective relationship between energy consumption and purified water quality [1].

Koutsou et al. investigated the effect of temperature in the range of 15 to 40°C on energy consumption. The obtained results showed that energy consumption was reduced in the brackish water RO. Moreover, in the seawater system, increasing the temperature causes osmosis pressure to increase. Thus, energy consumption was only reduced at 30°C. Furthermore, by increasing the temperature, salt rejection decreased in the Brackish and seawater system [45]. Alsarayreh et al. investigated Energy Recovery Devices (ERDs) on the energy consumption of APC via gPROMS software. The obtained results showed that energy consumption at the low feed flow rate, low pressure, and high temperature decreased [46]. Alanezi et al. investigated the effect of ERDs and pretreatment on the RO system. The obtained results showed that the RO system with ERD could be useful in case of high feed flow and low recovery value [47]. Choi et al. represented a novel concept of coupling Membrane Capacitive Deionization (MCDI) and reverse electrodialysis (RED) with two-pass RO to treat Brackish Water Reverse Osmosis (BWRO). Under optimized operation conditions, the obtained results demonstrated that the energy consumption of this RO-MCDI-RED hybrid system declined by 39.0%. Moreover, the energy consumption decreased to 16.8% compared to conventional two-pass RO systems without and with RED [48]. Choi et al. presented an energy-efficient hybrid desalination process for high-salinity brackish water. This novel design integrates Flow Capacitive Deionization (FCDI) with Nanofiltration (NF). The experiments and energy calculations illustrated that the energy consumption of the new FCDI-NF unit was 16 to 20% lower than the best reported energy consumption. Furthermore, the obtained results showed 1-stage practical minimum energy consumption of the BWRO unit treating the same feed at 70% water recovery, while the final TDSs were in the drinking water range [49]. Wang et al. proposed a hybrid RED/ED system for simultaneous osmotic energy recovery and complete desalination in the phenol-containing wastewater treatment process. Comparison of the obtained results with artificial seawater indicates that the high volume of power was generated using phenol-containing wastewater as the high-salinity stream. Their findings suggested that average power generation and limiting wastewater treatment capacity would provide insightful guidelines on the design and improvement of the hybrid system [50]. Qin et al. proposed system-scale models to analyze the energy consumption and energy efficiency of CDI and RO in a wide range of material properties and operating conditions. The results showed that at higher salinity feed streams and higher salt rejection values, RO was significantly more efficient than CDI. Furthermore, brackish water with a salt concentration of 2000 mg $L^{-1}$ and an average water flux of 10 $Lm^{-2}$ $h^{-1}$ achieved 50% water recovery and 75% salt rejection, respectively. Moreover, CDI required significantly Specific Energy Consumption (SEC), being more than eight times that of the RO [51]. Kim et al. investigated high SEC of Seawater Reverse Osmosis (SWRO). The analysis presented a large number of large-sized SWRO plants and reduced the SEC via isobaric ERDs. The obtained result showed that high salinity increased energy demand, whereas energy consumption was not affected by the temperature. In addition, high-efficiency ERDs and pumps could reduce SEC, but the overall SEC could not be examined by these factors alone. Furthermore, SEC was affected by target water quality and quantity [32]. Jeong et al. presented a numerical model for the 1-2 Energy-Efficient Reverse Osmosis (EERO) process and validated it with the data obtained from commercial RO projection software. The obtained results illustrated that under optimized conditions, the EERO process demonstrated not only greater energy efficiency (3–25%) but also conventional SSRO (Single-Stage Reverse Osmosis). Moreover, the EERO process achieved lower Concentration Polarization (CP) and potentials of membrane fouling than conventional SSRO for $\geq$ 55% overall recovery [52].

Despite various studies, the high energy consumption of RO systems on a sea scale as well as surface water is still a controversial concern and challenge in terms of using this technology. The objective of this research is to study the optimization of RO systems using a hybrid design (ISD), evaluate the temperature effect on efficiency, and compare energy consumption and efficiency in simple, multi-stage, and hybrid designs in the RO system. In the end, the analysis of membranes, the effects of temperature, Langjiller index, and the amount of chlorine and nitrate ions in purified water are examined.

## 2. Materials and simulation methods

### *2.1. Experimental data*

Simulation of 300 $m^3$/day RO system was evaluated in the south of Tehran. The purpose of desalination was to achieve fresh water with relevant standards. Table 2 shows the raw water extracted from wells from the south of Tehran and ions analysis [4].

### *2.2. Simulation method*

RO software was used for simulation. In the plant design, 12 membranes (8*40 inch) as well as three- and four-element PVs were used in different designs, including single-stage, two-stage, single-stage hybrid, and two-stage hybrid with two classes of BW 400 ES and BW 400 R. Figure 3 depicts a different design for an RO system.

## 3. Results and discussion

### *3.1. Temperature effect*

The effect of temperature on the Langelier index for the design of single-stage simple, hybrid RO systems, two simple, and hybrid stages is shown in Figure 4. As can be seen in Figure 4(a), by increasing the temperature, the Langelier index for different RO systems increases in value. Figure 4(b) also depicts the addition of a sodium hydroxide solution with pH = 9.2 to these systems. In Figure 4(a) and (b), it is clear that the treated output water moves away from the corrosive state by increasing the temperature. Increasing the temperature has increased the output efficiency of the membranes, which ultimately increased the number of ions in the water causing the system to avoid corrosion [37,44].

Figure 4(b) shows that adding sodium hydroxide to desalination causes the system to avoid corrosion quickly. Figure 5 shows that increasing the temperature due to increase in kinetic energy and decrease in the viscosity of water molecules increased the passage of water molecules through the membranes and increased the process efficiency. The efficiency of two-stage systems was much higher than that of the single-stage systems. Simple systems enjoyed higher efficiency than hybrid systems [42]. Therefore, the best desalination system was a simple system in terms of efficiency and it had higher efficiency even at 15°C than 35°C in a two-stage hybrid system. This phenomenon results from Net driving pressure (NDP) reduction and TDS increase in the water entering the BW 400 R membranes, which caused the efficiency of the BW 400 R membranes to decrease compared to the two BW 400 ES membranes. Therefore, the efficiency reduction for membranes led to decrease in the overall efficiency of the RO system in two-stage hybrid designs compared to the system with simple designs.

Figure 6(a) to (f) depict 3D graphs of the effect of temperature on single- and two-stage simple and hybrid efficiencies in terms of membrane number and the order

**Table 2.** Desalination feed compositions.

| TDS (ppm) | pH | Ca (ppm) | Mg (ppm) | Na (ppm) | K (ppm) | $NH_4$ (ppm) | $SO_4$ (ppm) | Cl (ppm) | $NO_3$ (ppm) | $SiO_2$ (ppm) | Ba (ppm) | $HCO_3$ (ppm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1592 | 7.24 | 138.4 | 89.76 | 350 | 2 | 0.03 | 525 | 355 | 18.7 | 30 | 0.06 | 0 |

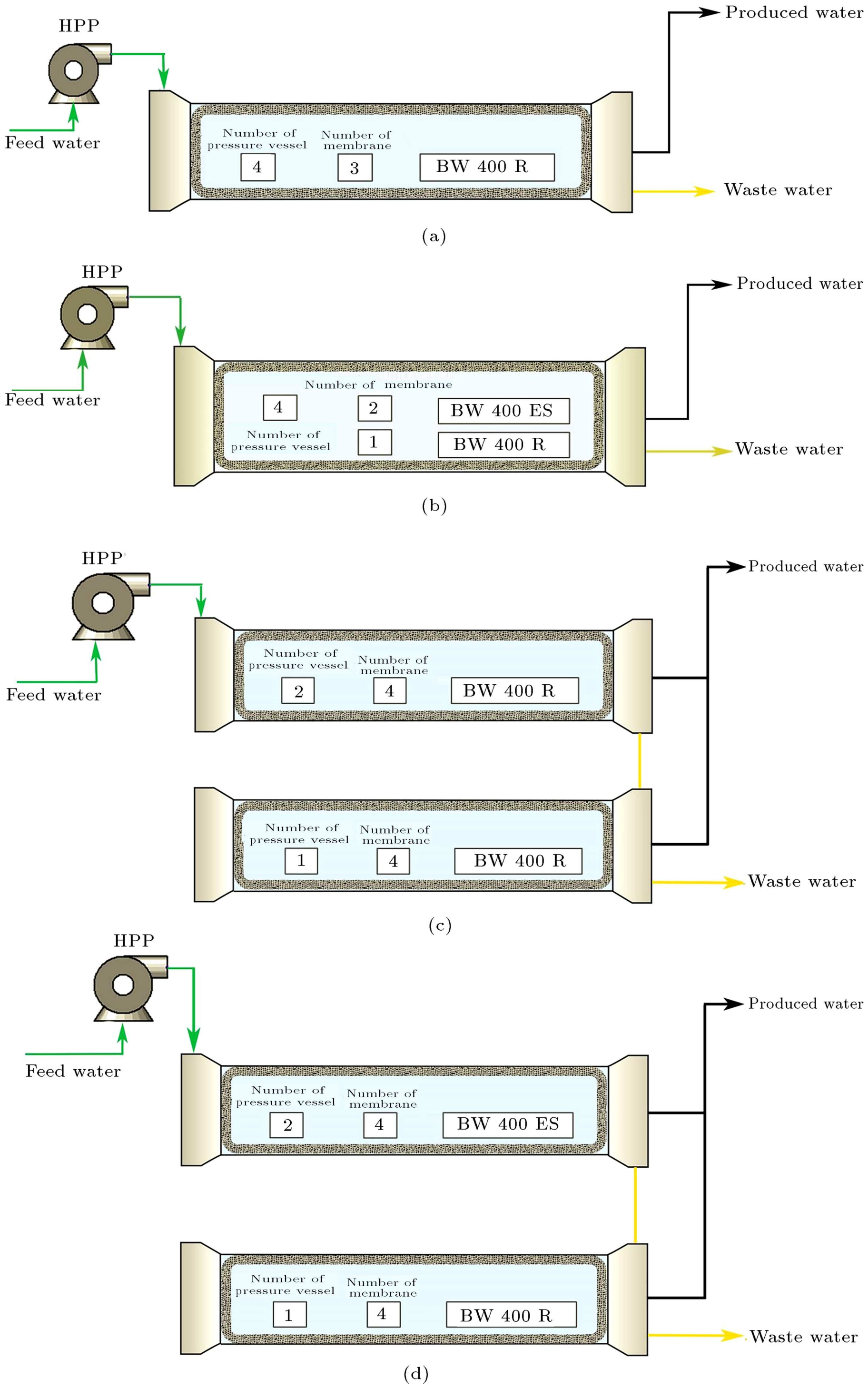


**Figure 3.** Schematic of the RO system in design for (a) simple single-stage, (b) single-stage hybrid, (c) simple two-stage, and (d) two-stage hybrid systems.

in which they are placed in the PV in RO systems. According to Figure 6(a) and (b), in a simple single-stage system, by increasing the number of membranes in the design, the efficiency of the membranes increased [37]. In Figure 6, the hybrid single-stage system experiences increase in the recovery rate in membranes 1 and 2, but the membrane efficiency decreased in membrane 3 at high pressure. The reason is that the ISD in this type of design uses a class of membranes with a higher percentage of solute removal at the beginning of the input to the PV, in other words, upstream. Moreover, membranes with a higher percentage of flux are used at the end of the PV, in other words, downstream. Another reason, as mentioned, is the NDP reduction

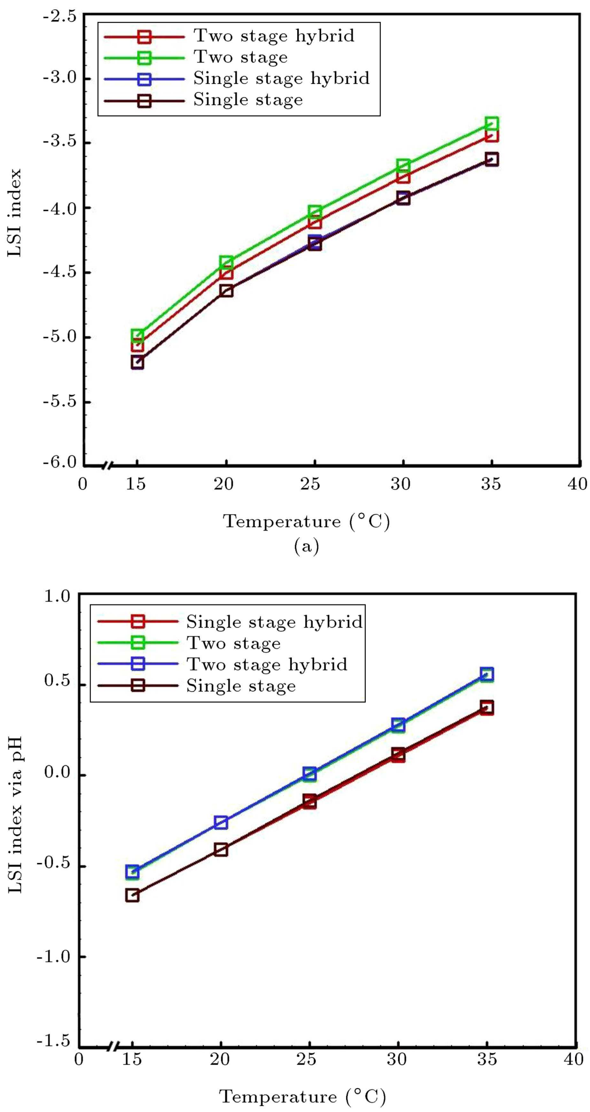


**Figure 4.** The effect of temperature on the Langelier index to design a single-stage simple, hybrid RO system, and two simple and hybrid stages: (a) Without the addition of sodium hydroxide and (b) with the addition of sodium hydroxide solution.

and TDS increase in the water entering the BW 400 R membranes, causing the efficiency of the BW 400 R membranes to decrease compared to the two BW 400 ES membranes.

Figure 6(c) and (d) showcase the simple two-step systems. These figures depict that in the first and second stages, by increasing the temperature and the

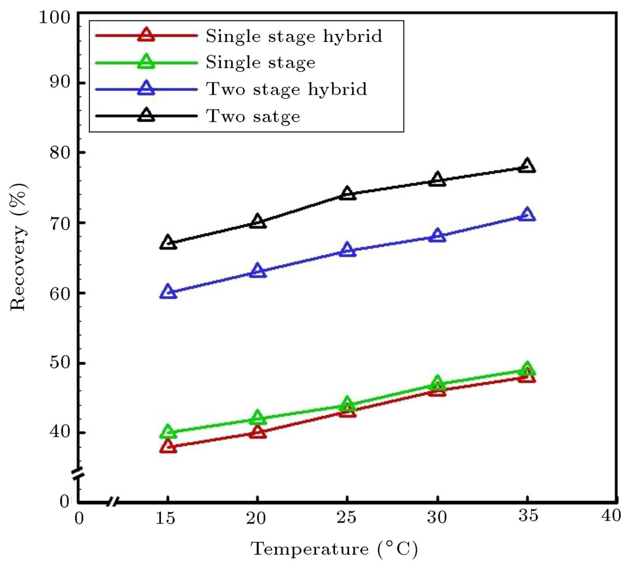


**Figure 5.** The effect of temperature on the efficiency of simple single-stage, single-stage hybrid, simple two-stage, and two-stage hybrid systems in RO.

number of membranes in simple two-stage systems, the efficiency increased. Figure 6(e) and (f) show the two-stage hybrid system. In the first and second stages of the two-stage hybrid system, the efficiency of the membranes increased upon increasing the temperature and the number of membranes. Because by increasing temperature, the kinetic energy and chemical potential of water molecules increased. This increase in chemical potential caused higher generation of driving force in the membrane and NDP high-pressure cell system than in the simple state system. The final reason is that as the temperature increased, the water viscosity decreased.

In other words, by increasing the temperature, the viscosity and stickiness of water and the flux passing through the membranes increase; consequently, the efficiency increases. Therefore, by increasing the temperature, the efficiency of both systems would increase. As can be seen in the simple and hybrid two-stage systems, the highest percentage of salt removal occurs in the first stage of the two-stage system. It is probably due to the increase in TDS feed in the second stage and the decrease in the pressure gradient for water molecules to pass through the membranes. As shown in Table 3, when the temperature increases, the efficiency rates of different systems get closer to one another. The efficiency ratio at low temperatures was higher than

**Table 3.** The amount of efficiency changes in different designs compared to the single-stage system.

| **Temperature (°C)** | **15** | **20** | **25** | **30** | **35** |
|---|---|---|---|---|---|
| Single stage hybrid vs. single stage | –5 | –5 | –2 | –2 | –2 |
| Two stage hybrid vs. single stage | +50 | +50 | +50 | +44.7 | +44.8 |
| Two stage vs. single stage | +67.5 | +66.7 | +68.2 | +61.7 | +59.1 |
| Two stag hybrid vs. two stage | -10.4 | –10 | –10.8 | –10.5 | –8.9 |

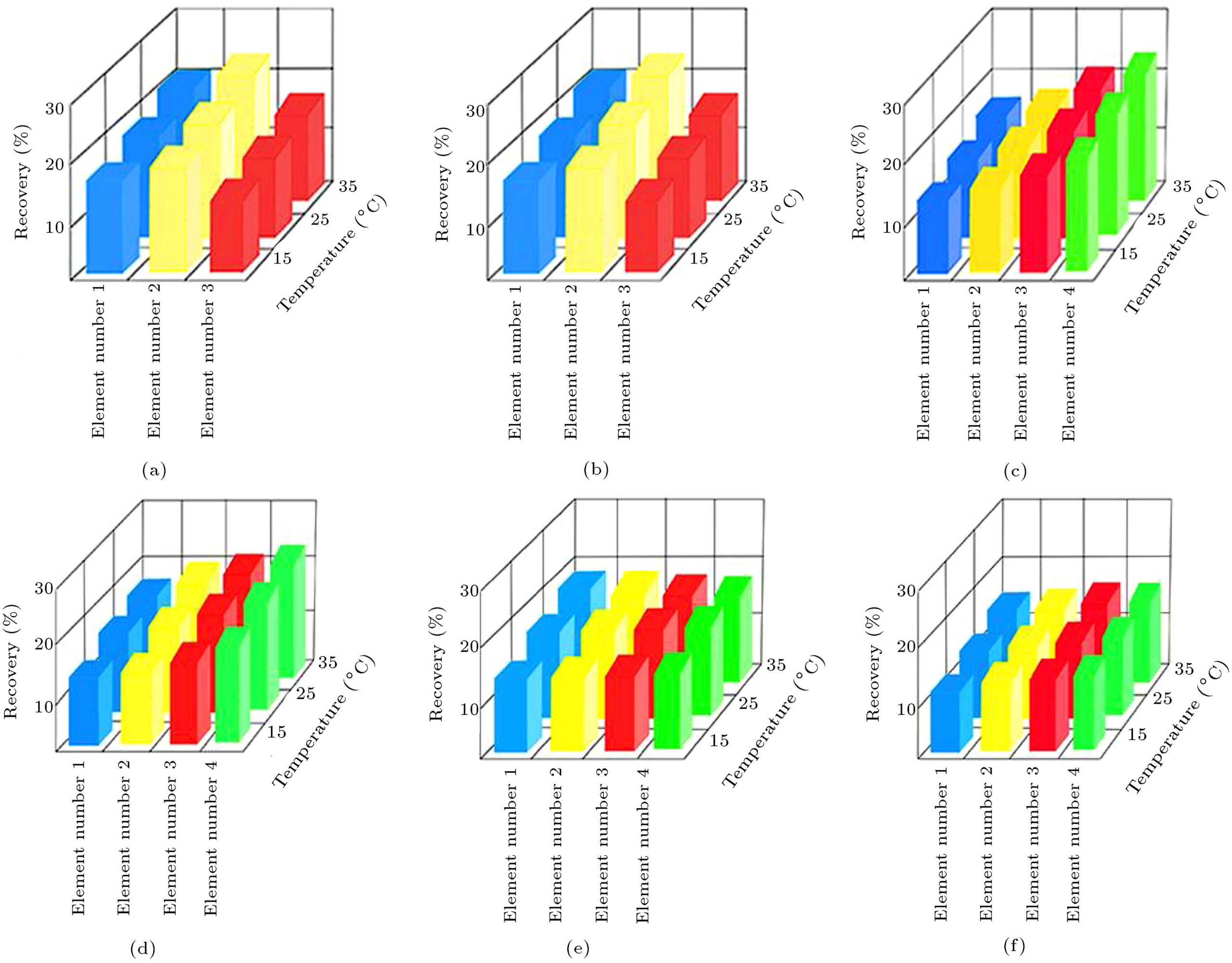


**Figure 6.** 3D graphs of the effect of temperature on the recovery for simple and hybrid systems: (a) Simple single-stage system, (b) hybrid single-stage system, (c) first stage of simple two-stage system, (d) second stage of simple two-stage system, (e) first stage of two-stage hybrid system, and (f) second stage of two-stage hybrid system.

that at high temperatures, indicating that increasing the temperature in systems with lower efficiency caused more upgrades. The single-stage hybrid system was compared to the simple single-stage system in the best condition, depicting a 2% reduction in inefficiency, while the two-stage hybrid system compared to the simple two-stage system at 35°C experienced an 8.9% reduction in efficiency. Therefore, choosing a high-temperature system for hybrid systems may be more appropriate than simple systems. In general, if only higher efficiency is considered in the RO process, the best option is to use a simple two-stage RO system. Moreover, the worst option is using a single-stage hybrid RO system.

Figure 7 represents the effect of temperature on the energy consumption of single and multi-stage configuration of simple and hybrid RO systems. Based on this figure, upon increasing the temperature, energy consumption of the RO system was reduced [37]. The reason for the above is that increasing the temperature

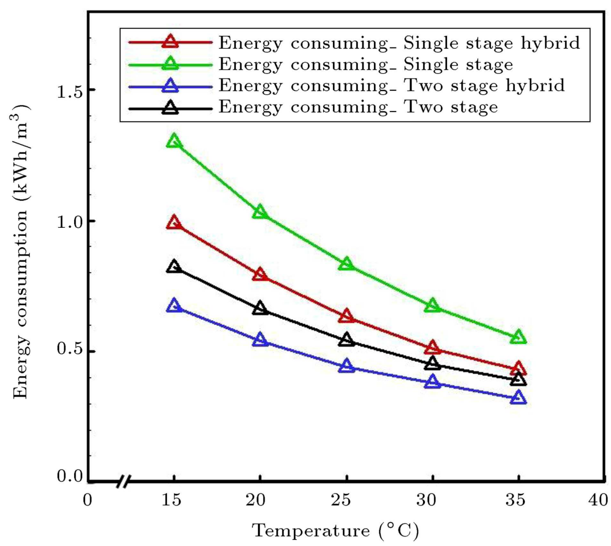


**Figure 7.** The effect of temperature on the energy consumption of single- and two-stage simple and hybrid systems.

would reduce the viscosity of water and increase the kinetic energy of the molecules; as a result, the flow of output water of the membrane pores increases. Therefore, much water can leave the membranes compared to the constant temperature condition, and a certain amount of pressure is removed from the membranes and the energy consumption of the RO system is reduced. It can also be seen that the energy consumption of the two-stage hybrid system had the lowest energy consumption compared to the simple single-stage and two-stage modes [1]. Since the hybrid systems had less sediment potential, fewer energy and washing processes would be required and the lifespan of the membranes would increase. Any increase in temperature has the greatest impact on the simple single-stage RO system and the least impact on the two-stage hybrid system. To design a desalination plant for the studied system, the best choice in terms of energy consumption is a two-stage hybrid RO system.

### *3.2. Energy optimization*

Figure 8 shows the energy saving of single- and two-stage simple and hybrid RO systems. As depicted in this figure, two-stage hybrid systems (ISD) feature more energy saving than the simple two-stage and single-stage hybrid systems [1]. From Table 4, it can be deduced that the energy saving of a two-stage system, two-stage hybrid system, and single-stage hybrid system compared to simple one-stage systems had the least rates of 29.2%, 41.8%, and 21.8%, respectively. The table also depicts that two-stage hybrid systems achieved 1.43 times more energy savings than simple two-stage systems while two-stage hybrid systems had 1.92 times more energy savings than single-stage hybrid systems in similar situations. Moreover, the systems in this table clearly show that the two-stage hybrid system has less energy consumption than other designs. Figure 9(a) and (b) examine the levels of dangerous and toxic ions of chlorine and nitrate in purified water, respectively. According to the figures, it can be seen that the simple and hybrid single-stage systems have better conditions than two-stage systems in the removal of chlorine and nitrate ions, because, in the second stage, two-stage systems produced more TDSs. Therefore, the sum of TDSs in the first and second stages increased the TDS of the output product [41]. In addition, the amount of chlorine and nitrate ions in simple- and hybrid two-stage systems was more than that in simple and single-stage hybrid systems. Following an increase in the temperature, the concentration of chlorine and nitrate ions increased for all the four systems [44]. These figures show that the performance of simple single-stage RO systems and hybrid single-stage is almost similar, given the overall efficiency.

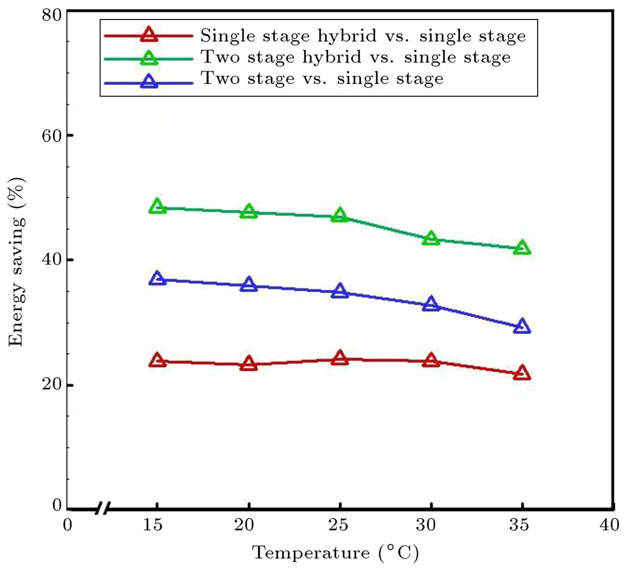


**Figure 8.** The energy-saving rate of single- and two-stage simple and hybrid RO systems.

However, the two-stage hybrid RO system outperformed the simple two-stage removal of chlorine and nitrate ions. In other words, in hybrid systems, the removal percentage was higher and the water quality was better, with lower efficiency [1]. This phenomenon was due to the reduction of NDP of the two-stage membranes compared to the one-stage ones, which reduced the efficiency of the two-stage hybrid system compared to the efficiency of the simple two-stage system. Therefore, the overall efficiency of the two-stage hybrid system was reduced compared to the simple two-stage one; as a result, the amount of chlorine and nitrate output was reduced.

### *3.3. Effect of water pH*

Figure 10(a) and (b) show the effect of the pH of the water entering the desalination system on the energy consumption and efficiency of different RO systems. As can be seen from this figure, any changes in pH of the given feed had minor effect on the efficiency and

**Table 4.** The amount of energy-saving of different designs compared to a simple single-stage system.

| Temperature (°C) | 15 | 20 | 25 | 30 | 35 |
|---|---|---|---|---|---|
| Single stage hybrid vs. single stage | 23.8 | 23.9 | 24.1 | 23.8 | 21.8 |
| Two stage hybrid vs. single stage | 48.4 | 47.6 | 47 | 43.3 | 41.8 |
| Two stage vs. single stage | 36.9 | 35.9 | 34.9 | 32.8 | 29.2 |

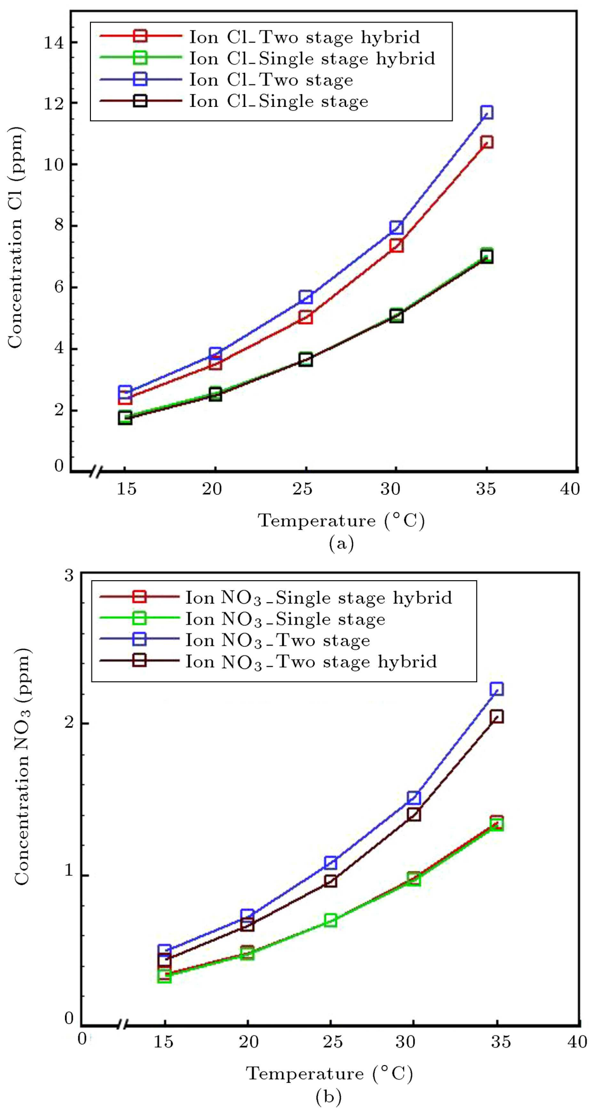


**Figure 9.** The effect of temperature on the number of ions of output product in single-, two-stage simple and hybrid RO systems for (a) chlorine and (b) nitrate.

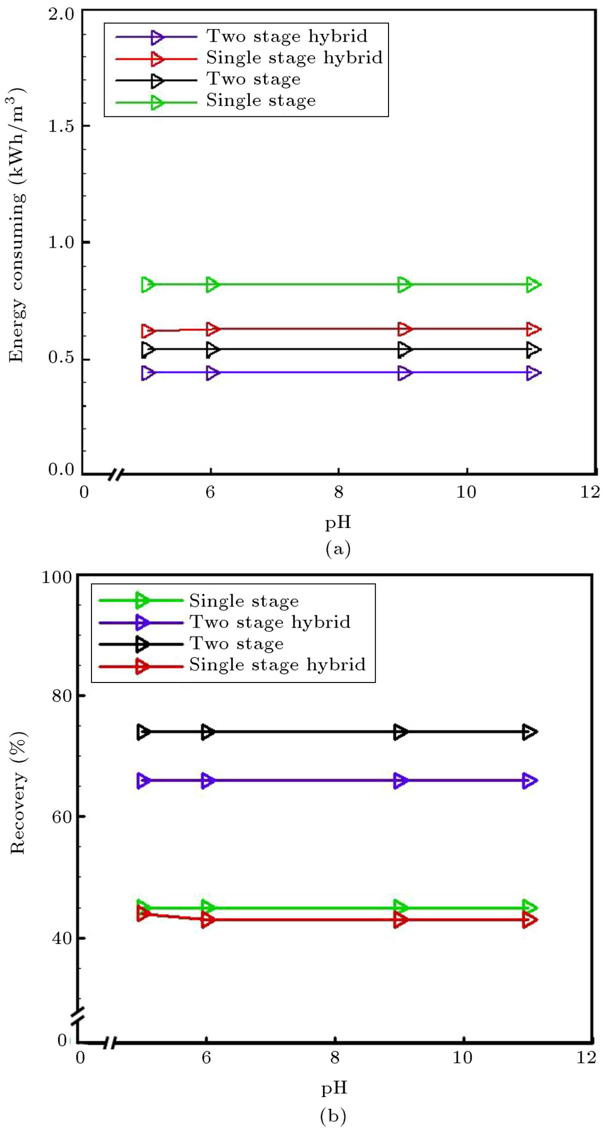


**Figure 10.** The effect of input water pH on (a) energy consumption and (b) efficiency of different RO systems.

energy consumption of RO systems, and the addition of substances such as sodium hydroxide or acid to the system did not change the system energy consumption or overall process efficiency.

### *3.4. Effect of operating pressure*

Operating pressure values in the Brackish RO system are given in Figure 11. This figure shows that with increase in the temperature, operating pressure deceases. Moreover, the RO system with different membranes is subjected to lower operating pressure than the simple system.

## 4. Conclusion

This study investigated the impact of the temperature on different design parameters such as efficiency, energy consumption of the Reverse Osmosis (RO) system, number of harmful ions in the product water, and Langelier index. The simulation results indicate that by increasing the temperature and pH index, the value of Langgiller index for single, two-stage simple, and hybrid RO systems in the simple mode increased. In addition, by increasing the temperature of the water, the flux of water leaving the membrane pores and the overall efficiency increased due to significant chemical potential and decreasing the viscosity of water in the membranes. Analysis of BW 400 ES and BW 400 R membranes in different designs represented that in the case of two-stage, two-stage hybrid and simple single-stage systems, with increase in the number of membranes and addition of the pressure vessel, the efficiency of the membranes at each design phase increased as temperature increased. In terms of energy saving,

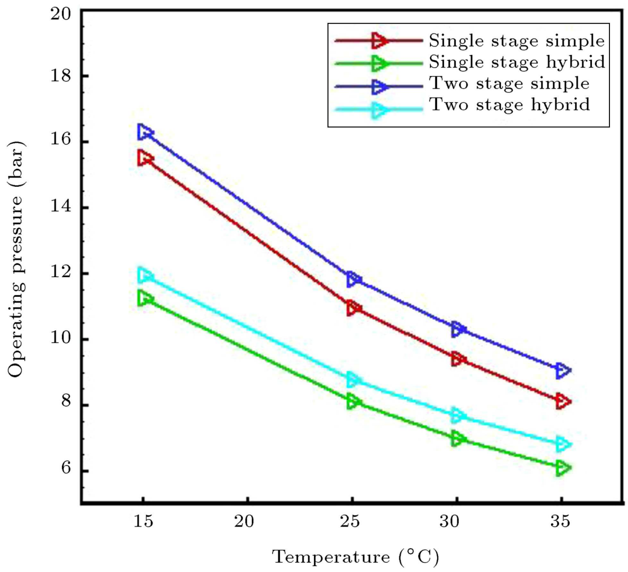


**Figure 11.** The effect of temperature on the operating pressure in single- and two-stage simple and hybrid RO systems.

hybrid systems had better performance than similar simple systems, but in terms of efficiency, simple RO systems performed better than similar hybrid modes. The findings also demonstrated that the pH of water entering the RO system did not affect the efficiency and energy consumption. Moreover, the removal rate for nitrate and chlorine ions in single- and two-stage hybrid (ISD) designs was higher than that for RO systems with simple single and two-stage designs.

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