AUT Journal of Mechanical Engineering

AUT J. Mech. Eng., 8(2) (2024) 109-122
DOI: 10.22060/ajme.2024.22913.6084

Experimental study of thermal gradient effect on reverse osmosis process

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ABSTRACT: In the present work, an experimental study of the thermal gradient effect on the reverse osmosis process is performed to evaluate pure water penetration and water production under the effect of the temperature gradients and the salt concentration. The experimental study uses a novel experimental setup designed and built for the present work. The Reverse Osmosis membrane was used in the experimental setup. The results showed that this process is dependent on salt concentration and temperature gradient between permeate-water and saline-water sides. It is observed that in 10.8°C temperature difference between the permeate-water and the saline-water part for 1 gr/lit salt concentration at saline-water part, the Process time is 20 min, water flux is 0.142 kg/(m^2 s) and salt concentration in the saline-water part varies from 1.04 gr/lit to 1.22 gr/lit. In addition, for a 1.5°C temperature difference between the permeate-water part and the saline-water part for 1 gr/lit salt concentration at the saline-water part, the Process time is 35 min, water flux is 0.043kg/(m^2 s) and salt concentration in the saline-water part varies from 1.004 gr/lit to 1.059 gr/lit. It can be concluded, that while the temperature gradient increases, the Process time decreases, and pure water penetration from saline-water to permeate-water part also increases. As a result, the salt concentration and electrical conductivity can increase in the saline-water part.

Review History:

Received: Jan. 07, 2024
Revised: Jul. 10, 2024
Accepted: Jul. 14, 2024
Available Online: Jul. 24, 2024

Keywords:

Experimental Study
Reverse Osmosis
Thermal Gradient
Salt Concentration
Electrical Conductivity

1- Introduction

The lack of usable water for various uses, including drinking, irrigation, industry, and other usages due to increased consumption and impurities of available pure water sources, has caused a significant increase in water desalination. Water desalination includes separation processes that generate pure water from seawater and other polluted water resources that are inappropriate for use [1]. Water desalination is accomplished by various of technologies that are modified to reduce capital costs, energy, and other impacts [2]. Water shortage is one of the most critical problems in the world. In many areas, their shared water resources are unsuitable for population growth and industrialization [3]. By 2025, 1.8 billion people expect to live in areas with insufficient water resources [4]. Desalination of seawater or other non-potable water is used to overcome water shortage problems [5]. Currently, reverse osmosis is one of the most essential and accountable methods for the development of desalination, which produces pure water without pollutants and other particles [6]. The RO desalination method is a significant advance in membrane development, module and process design, and energy recovery from a commercial point of view [7]. Desalination methods can be divided by two factors: energy source (thermal, mechanical, electrical, and chemical energy) and desalination process (evaporation-condensation, filtration, and crystallization method) [2]. The shortage of energy resources causes the development of desalination systems by renewable energy [8].

RO desalination technology is used to purify Seawater and Brackish water. The RO desalination energy consumption is 3.5 to 5 kWh/m^3. The RO desalination technology advantage over other desalination technologies (like multi-stage flash desalination, multi-effect desalination, and thermo-vaper compression) is that this process is carried out at ambient temperature and needs no thermal energy [9].

2- Reverse osmosis desalination: concepts and considerations

Osmosis is a process in which pure water moves from a low-concentration solution to a more concentrated solution by using a membrane element [10]. Some methods like energy recovery turbines and pressure exchangers are used for energy recovery in the reverse osmosis desalination process [11]. Nowadays, reverse osmosis is the most important desalination method which is preferred over other desalination methods[12]. In many factories, reverse osmosis is used for water refineries [13]. Advances in membrane material and energy recovery in the past three decades have reduced the energy expenditure of water production [14].

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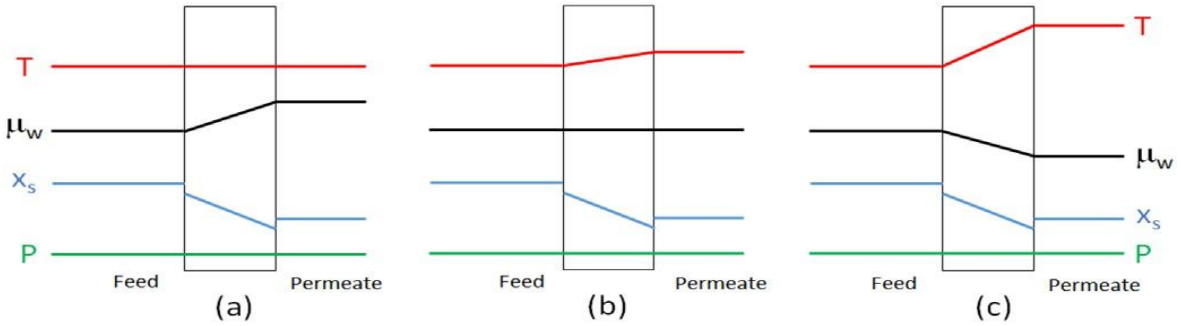


Fig. 1. Temperature (T), water chemical potential (μ_W), solute concentration (XS), and pressure (P) among the active membrane layer for three cases of temperature-driven mass transfer; (a) forward osmosis, (b) osmotic equilibrium, (c) reverse osmosis [20].

New studies on reverse osmosis desalination focus on improving the membrane structure [15]. Modifications include improvement of the membrane surface with organic cover to decrease fouling, and the hydrodynamic design of modular membrane elements to enhance capacity [16,17].

New technological advances have decreased the unit price of pure water. However, these developments will lead to an increase in the cost of capital [18, 19].

3- Temperature driven reverse osmosis: Concept and definition

The osmosis process is dependent on three parameters. These three parameters are temperature, pressure, and chemical potential. Fig. 1 shows three states that happen in the osmosis process. When temperature and pressure are constant (Fig. 1a), chemical potential from the permeate-water to the saline-water side causes water diffusion by osmosis. When the permeate-water side has a higher temperature versus the saline water part, the chemical potential for water flux decreases and causes less water diffusion.

Osmotic equilibrium can occur at a threshold temperature, where the chemical potential of water is the same on each side of the membrane (Fig. 1b). If the permeate-side temperature is increased further then a chemical potential gradient is created in the opposite direction, leading to reverse osmosis (Fig. 1c).

One of the parameters that can create the force for pure water diffusion from saline water to permeate water is the temperature gradient. This temperature gradient can dominate the osmotic pressure and create a driving force along a membrane. A temperature difference of less than one degree Celsius between permeate-water and saline water is required to dominate the osmotic pressure, and about three degrees Celsius to maintain a water diffusion equal to standard reverse osmosis processes. By using temperature gradient instead of pressure difference, it is predicted that the energy requirement will be reduced to less than two kwh⁄m^3 [20].

The principle of using a slight temperature gradient along a membrane and its diffusion properties have been studied by Lee et al. [21]. In temperature-driven reverse osmosis, it is assumed that the pressure difference between the saline water and the permeate-water part is negligible. In this process, temperature and salt concentration differences between the saline water and the permeate-water part act as a driving force. At each specified salt concentration, by increasing the temperature gradient between the permeate-water and saline-water parts, the driven force is increased. As a result, pure water diffusion from the saline water part to the permeate water part increases.

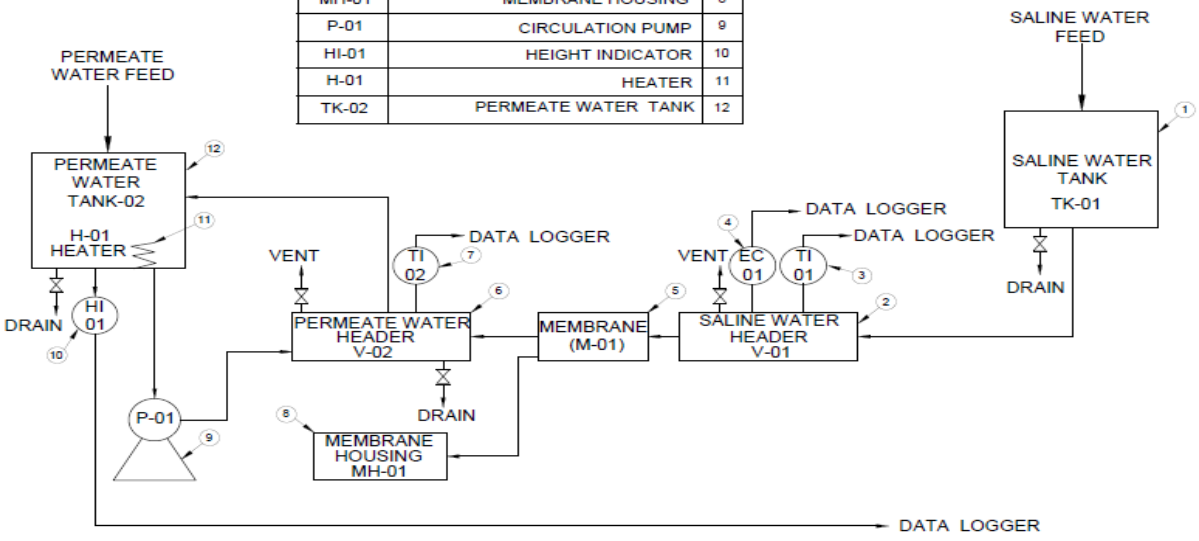
3- 1- The advantages of temperature-driven reverse osmosis

RO desalination technology needs energy for high-pressure pumps, but in temperature-driven reverse osmosis, the process is done by finite temperature gradient. So, the energy consumption and the equipment size are reduced. Temperature energy-driven reverse osmosis can be supplied from reproducible energy like solar energy. The energy can also be supplied from excess energy like warm water, and low-pressure steam.

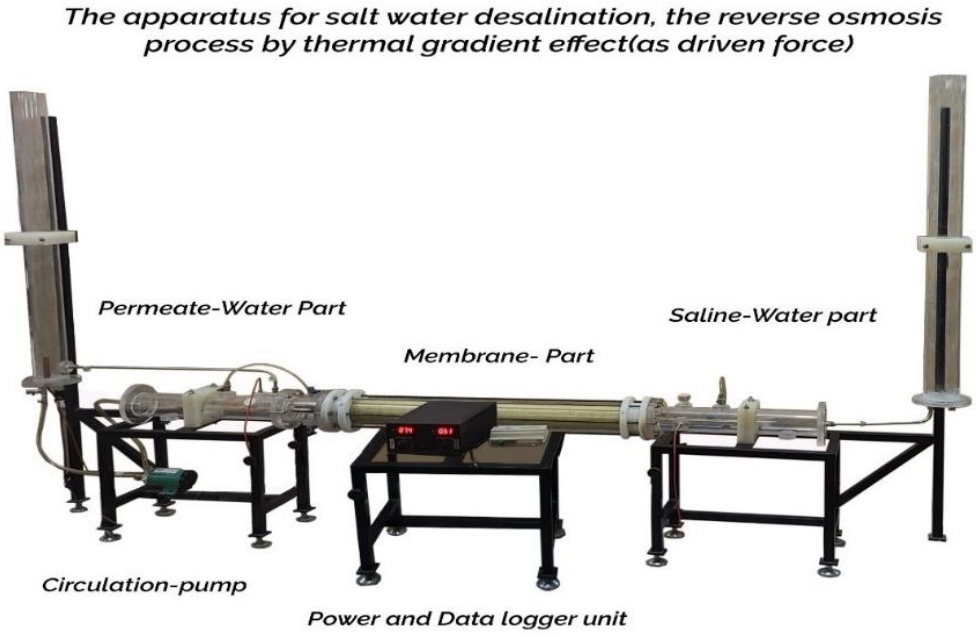
4- Experimental setup

Fig. 2a and Fig. 2b present the P&ID diagram and apparatus of the temperature-driven reverse osmosis with layout details. This apparatus consists of two main parts, the saline-water part and the permeate-water part. Saline-water part consists of a vertical vessel, a horizontal header, a steel metal frame, connecting pipe, instruments, and a drain and vent tapping. The permeate water part consists of a vertical vessel, a horizontal header, a steel metal frame, connecting pipe, instruments, and a drain and vent tapping. Saline and permeate water parts are connected to each other by a membrane and a membrane vessel by bolts and nuts. Temperature and electrical conductivity on the saline part as well as the level of permeate water are measured and sent to the data logger. Thermometers on saline and permeate water

PART NO.	DESCRIPTION	ITEM NO.
TK-01	SALINE WATER TANK	1
V-01	SALINE WATER HEADER	2
TI-01	TEMPERATURE INDICATOR	3
EC-01	ELECTRIC CONDUCTIVITY METER	4
M-01	MEMBRANE	5
V-02	PERMEATE WATER HEADER	6
TI-02	TEMPERATURE INDICATOR	7
MH-01	MEMBRANE HOUSING	8
P-01	CIRCULATION PUMP	9
HI-01	HEIGHT INDICATOR	10
H-01	HEATER	11
TK-02	PERMEATE WATER TANK	12



(a)



(b)

Fig. 2. Experimental Set up
(a) P&ID diagram Temperature driven reverse osmosis apparatus(b) Experimental Set up picture

parts are in PT-100 type.

A permeate water tank and a saline water tank are connected to a hot and cold water header according to Fig. 2. The hot-water header has an inlet and outlet connection and a circulation pipe to the heated tank. The hot water tank is connected to the inlet of the circulation pump. The outlet of the circulation pump is connected to the hot water header. The variable heater is placed in a permeate tank. The saline-water part consists of a saline-water tank, saline-header, and membrane housing. The saline-water tank is connected to a saline-water header by a stainless steel pipe. This connection between the saline-water tank and the saline-water header can help to ensure the membrane housing is always full of water. This minimizes the pressure difference between the two parts. The entire membrane housing is immersed in cold water to act as a heat sink, this helps to maintain a sufficient temperature gradient along the membrane.

The device is powered by 220 and 24 volts. The pump circulates the water in the permeate water part. The heater is placed at the bottom of the permeate water vessel and heats permeate water. The heating rate of the heater is controlled by variable control power.

A membrane (Type of DOW Filmtec SW30HR) was used in the experimental setup. The membrane is maintained between the flanges of a four-inch Plexiglas pipe. A pump circulates the flow between the tank and the header of the permeate-water part.

5- Experimental procedure and measuring equipment

To start the experimental procedure, a specific volume of the permeated water and the saline water with a specified salt concentration is prepared. Water used for the experimental procedure should be free of chlorine ions because chlorine ions damage membrane elements. The saline water and the permeate-water parts are filled with an initial volume of five liters simultaneously. The temperature and conductivity are measured at a specified tapping on headers (10 cm from the end flange of permeate-water and saline-water header.). The Saline-water and the permeate-water part are filled at the same time. It is caused by the no-pressure difference between the permeate-water and the saline water part is created.

After filling the permeate-water and the saline-water part, the heater and circulation pump on the permeate-water part are started. The circulation pump creates a uniform temperature between the permeate-water tank and the permeate-water header. By creating a temperature difference between the permeate water and the saline-water side, the permeate water diffuses from the saline water to the permeate water part. It causes the permeate water level and salt concentration on saline water part are increase.

Temperatures of the saline water part and permeate-water part are measured continuously by TP-100 thermometers and the result is sent to the data logger. Temperature probes have a resolution of ± 0.1 °C with +/- 2% accuracy.

Also, the electrical conductivity for the saline water part is measured by using a 0 to 4000 µS/cm probe (Hanna Instruments HI- 99300). This probe is placed in a specified tapping on the saline-water header. The conductivity probe has a resolution of 1 µS/cm and an accuracy of +/- 2%. A conductivity probe is used to provide an accurate reading to detect small changes in concentration. The Saline concentration is determined with a predetermined calibration at 15 °C:

$$EC = 1728X + 612 \quad (1)$$

The process ends when the electrical conductivity of the saline water part is constant. After this time no change in the saline water part is observed.

For confidence in the process time, each experiment for certified salt concentration and temperature difference between the permeate water part and the saline water part is done several times and the results are checked.

To ensure the accuracy of experimental results, permeate-part header conductivity is measured at the beginning and end of each experiment. By using the variable heater, the temperature difference between the hot water and the cold water part is maintained at a specific range. This experiment is repeated for different temperatures and salt concentrations.

At the end of the process, by considering the change in permeate water tank height, the rate of diffusion of pure water from the saline water part to the permeate water part is calculated. By multiplying the change of permeate water tank height on the permeate-water tank by area, the volume of diffused pure water is obtained. By dividing the mass of this volume on the inside area of the membrane and dividing it by the elapsed time, the water flux is obtained. For checking the pure water production, the change of salt concentration in the saline water part can be evaluated.

Each experimental procedure has some errors arising from human and equipment errors. To decrease these errors, experimental results are compared with other experimental work [20]. Comparison with previous work certifies that the experimental procedure and results are exact.

The experimental results are compared with Ref. [20]. For comparison, the experiments for different NaCl concentrations and temperature gradients between the permeate-water and the saline-water part are done. Comparisons between the present work and Ref. [20] are shown in Table 1. According to Table 1, it is observed that between Ref. [20] and the present experimental mass flux, the variations are between 1.9% to 4.5%. Thus, there is an acceptable matching between Ref. [20] and the present work. Therefore, the experimental data is valid and other tests can be performed to obtain the required results.

6- Results and discussion

By using the setup and experimental procedure as described in 4,5 sessions, the following results for different temperature differences between permeate-part and saline-part in different salt concentrations are obtained. All measured saline part conductivities are corrected at 15°C (because salt concentration was computed by a predefined calibration at

Table 1. Comparison for diffusion between Ref. [20].and present experimental work

		Robinson et al.'s work	Present work	Difference between the results of Robinson et al. and Present work	Variation %
ΔT_{avg}	NaCl conc.	Max Mass flux	Max Mass Flux	Max Mass Flux	
^{0}C	g/l	$\times 10^{-3} kg/m^2.s$	$\times 10^{-3} kg/m^2.s$	$\times 10^{-3} kg/m^2.s$	%
0	1	-0.111	-0.106	0.005	4.5
1.5	1	44.6	43.7	0.9	2.01
2.5	1	50.1	49	1.1	2.2
10.8	1	145	142.2	2.8	1.93
0	0.35	0.111	0.106	0.005	4.5
1.5	0.35	31.1	30.5	0.6	1.92
9.3	0.35	80.0	78.5	1.5	1.9

Table 2. Experimental data for delta Tave=10.8oC , Salt Concentration=1 gr/liter

			Saline-part conductivity		Salt concentration	
Time	Permeate water temperature	Saline-part temperature	Measured	Corrected to 15°C	From calibration	Uncertainty
minute	°C	°C	µS/cm	µS/cm	g/liter	g/liter
0	20	9.95	2200	2422	1.04	0.027
3	19.6	10.27	2284	2500	1.09	0.028
7	19.8	10.09	2377	2610	1.16	0.030
11	19.5	10.36	2471	2700	1.18	0.031
14	19.5	9.82	2491	2715	1.21	0.031
20	19.7	11.04	2518	2717	1.22	0.032

15°C). The saline part concentrations are obtained from the saline part conductivities by using Eq. (1).

In Table 2 the experimental data for the 10.8°C average temperature difference between the permeate-water and the saline water part with salt concentration of (1 gr/lit) are shown. As seen in Table 2, the process is ended at 20 min. After this time, no variation in saline-part conductivity was viewed. The saline-water part conductivity and saline-water part concentration variation are summarized in Table 5.

In Table 3 the experimental data for the 9.3°C average temperature difference between permeate-water and saline-water parts with salt concentration of (0.35 gr/liter) are shown. According to Table 3, the process ended at 28 min. After this time, no variation in saline-part conductivity was viewed.

In Table 4 the experimental data for different average temperature gradients between the permeate-water and the saline-water part with different salt concentrations are shown. In Table 4, the total time of the process varies from 20 min to 120 min. By considering the total time of process and water production, it observes that the end time of the process is dependent on two factors, 1: salt concentration and 2: average temperature gradient between the permeate-water and saline-water part. By increasing each of the two factors, the end time of the process decreases, and water production increases.

For checking the no salt diffusion between the permeate-water and the saline-water part, the permeate-part conductivity is measured at the beginning and the end of the

Table 3. Experimental data for delta Tave=9.3oC, Salt Concentration=0.35 gr/liter

			Saline-part conductivity		Salt concentration	
Time	Permeate water temperature	Saline-part temperature	Measured	Corrected to 15°C	From calibration	Uncertainty
minute	°C	°C	µS/cm	µS/cm	g/liter	g/liter
0	23.8	14.5	1212	1224	0.354	0.007
3	23.8	14.5	1224	1236	0.361	0.007
7	23.8	14.5	1236	1248	0.368	0.007
11	23.8	14.6	1248	1258	0.373	0.007
14	23.8	14.6	1260	1270	0.380	0.008
17	23.9	14.7	1272	1280	0.386	0.008
20	23.9	14.7	1282	1290	0.392	0.008
23	23.9	14.7	1290	1298	0.396	0.008
26	24	14.8	1300	1305	0.401	0.008
28	24.2	15	1307	1308	0.402	0.008

Table 4. Experimental data for the beginning and the end of permeate-part conductivity and overall water production

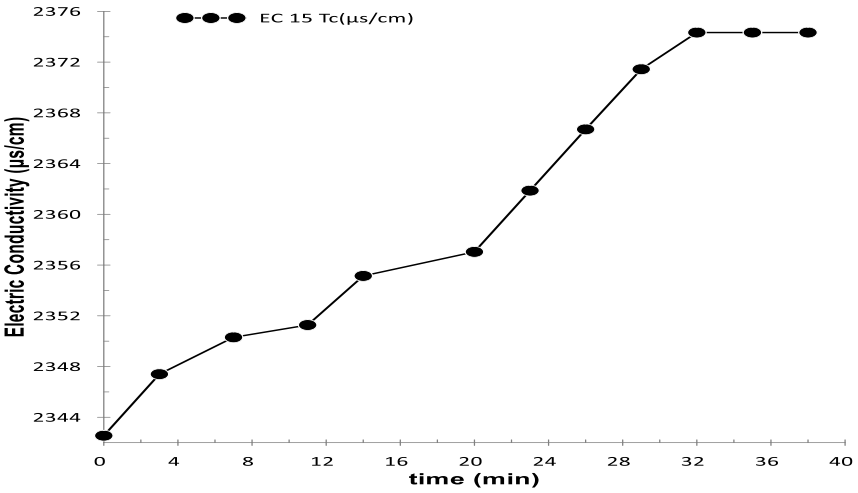
			Beginning permeate-part conductivity		End permeate-part conductivity		Water production
ΔT_{avg}	NaCl conc.	Total time	Measured	Corrected to 15°C	Measured	Corrected to 15°C	
°C	g/l	min	µS/cm	µS/cm	µS/cm	µS/cm	l
1.5	1	35	630	668	626	667	0.197
2.5	1	20	630	642	617	640	0.229
10.8	1	20	630	668	626	668	0.8136
1.5	0.35	120	630	630	645	630	0.112
9.3	0.35	28	717	612	737	612	0.6592

process. Measured and corrected permeate-part conductivities at 15°C are reported in Table 4. By comparison between the beginning permeate-part conductivity and the end permeate-part conductivity values, it can be seen the variation is negligible. Therefore, it can be concluded that the process is done correctly and no diffusion from the permeate-water to the saline-water part has occurred. By considering Tables 2,3 and 4, it is observed that by increasing the saline-water part concentration and temperature gradient, the driving force for the process increases. According to this increase, the process time decreases and pure water penetration from the saline-water to the permeate-water part increases. As a result, the variations of electrical conductivity and salt concentration increase in the saline-water part. The water production quality is described in Table 5.

The experimental results for three different average temperature gradients between permeate-water and saline-water parts with a salt concentration of (1 gr/lit) are plotted. In Figs. 3, 4, and 5 Process time, saline-water part conductivity, and salt concentration variations are summarized in Table 6.

The experimental results for two different average temperature gradients between permeate-water and saline-water parts with a salt concentration of (0.35 gr/lit) are plotted. In Figs. 6 and 7 Process time, saline-water part conductivity, and salt concentration variations are summarized in Table 7.

By considering the results shown in Figs. 3 to 7, it is concluded that at the same saline-part concentration, the increasing temperature gradient between the permeate-water and the saline-water part process time reduces, and saline-water part concentration increases. Therefore, it



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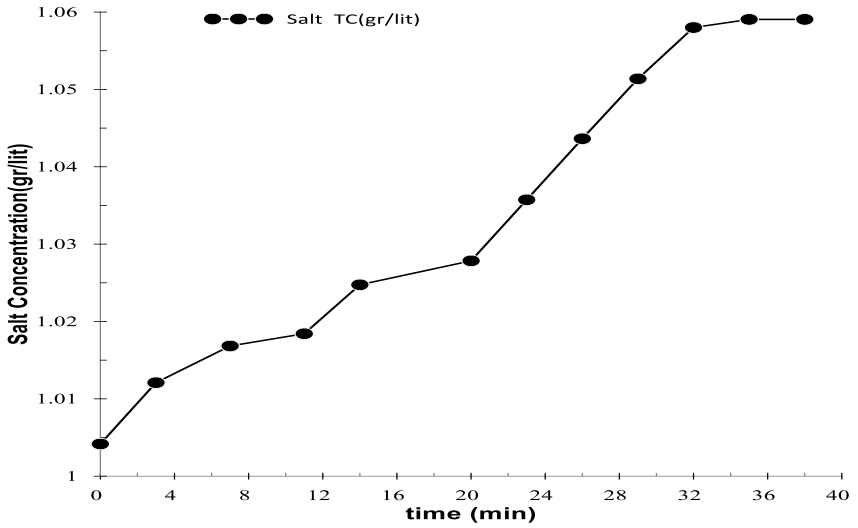

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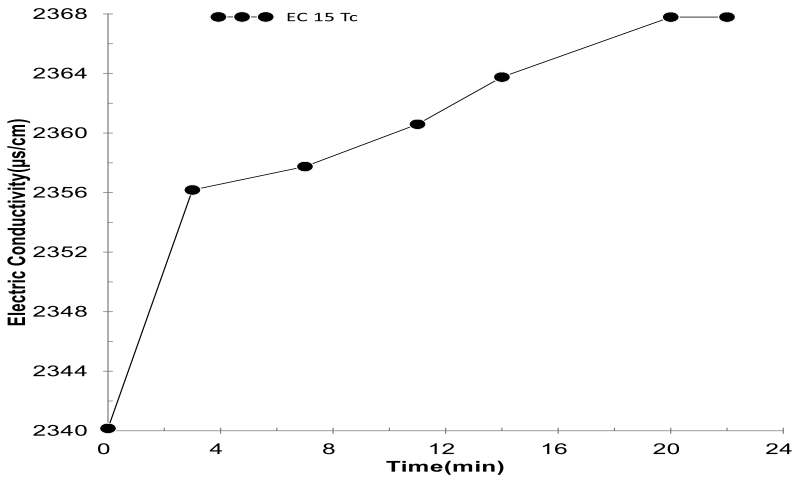
Fig. 3. Temperature gradient=1.5 Celsius degree, Salt concentration=1 gr/liter (a)Electrical Conductivity(µs/cm) (b)Salt Concentration(gr/liter)

can be concluded that the penetration rate increases. Thus, the penetration rate and process time are dependent on the temperature gradient between the permeate-water and the saline-water part.

By considering salt concentration and electrical conductivity versus time, it is observed that the rate of variation at the beginning of the procedure is more significant than at the end of the procedure. Also, observed that each chart can be divided into three parts. In the first part, the variation rate is the fastest than the other parts. By spending time, the variation rate is reduced. At the end of the process, the variation slope converged to a straight line. For each condition, data are plotted for a more extended time. Unlike the pressure reverse osmosis process, the temperature-driven reverse osmosis process is completed after a specified time. This specified time for each condition is different. Experimental data showed that after a specified time, no variation in parameters occurred. When the electrical

Table 5. Experimental data for water production conductivity and concentration

		Water production conductivity			Water production concentration
ΔT_{avg}	NaCl conc.	Total time	Measured	Corrected to 15°C	
°C	g/l	min	µS/cm	µS/cm	g/l
1.5	1	35	620	660	0.027
2.5	1	20	612	652	0.023
10.8	1	20	600	630	0.010
1.5	0.35	120	615	628	0.009
9.3	0.35	28	600	618	0.003



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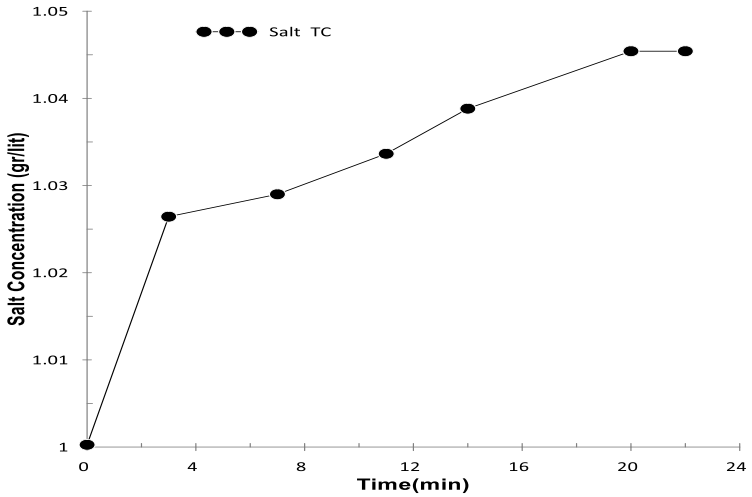
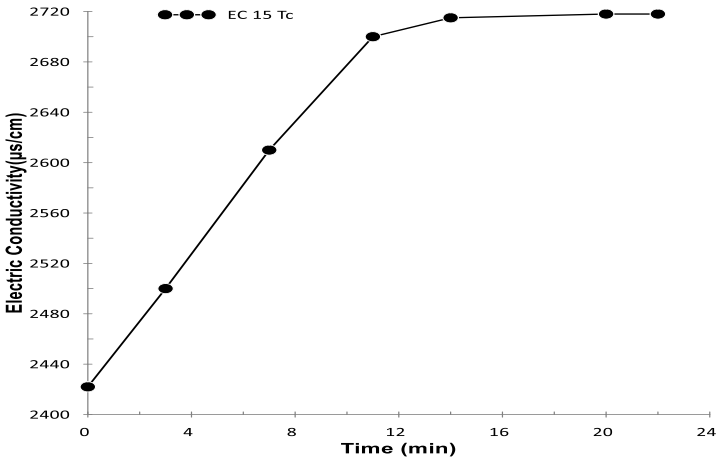


(b)

Fig. 4. Temperature gradient=2.5 Celsius degree, Salt concentration=1 gr/liter (a)Electrical Conductivity(µs/cm) (b)Salt Concentration(gr/liter)

Table 6. Experimental data for different delta Tave, Salt Concentration=1 gr/liter

		Saline-water part conductivity		Saline-water part Salt concentration	
Average temperature difference between permeate-water part and saline-water part	Process Time	Beginning	End	Beginning	End
°C	minute	µS/cm	µS/cm	g/liter	g/liter
1.5	35	2343	2376	1.004	1.059
2.5	20	2340	2368	1.000	1.045
10.8	20	2422	2717	1.04	1.22



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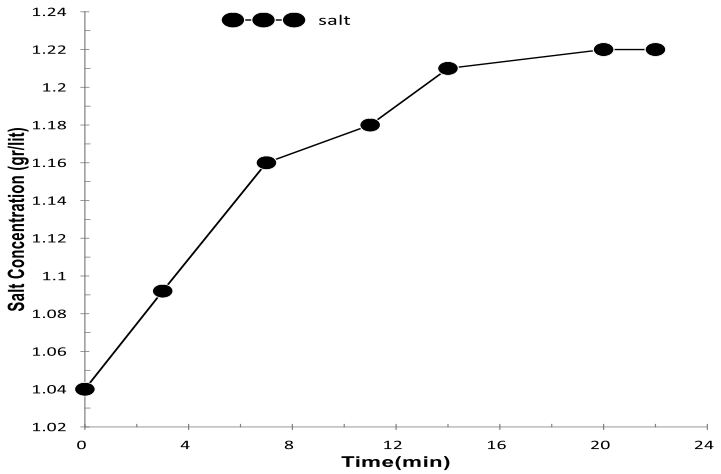

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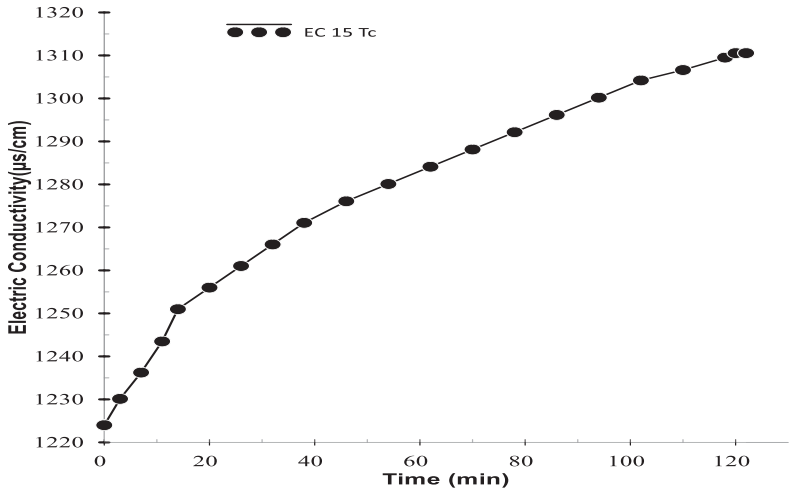
Fig. 5. Temperature gradient=10.8 Celsius degree, Salt concentration=1 gr/liter (a)Electrical Conductivity(µs/cm) (b)Salt Concentration(gr/liter)

Table 7. Experimental data for different delta Tave, Salt Concentration=0.35 gr/liter

		Saline-water part conductivity		Saline-water part Salt concentration	
Average temperature difference between permeate-water part and saline-water part	Process Time	Beginning	End	Beginning	End
°C	minute	µS/cm	µS/cm	g/liter	g/liter
1.5	120	1224	1308	0.354	0.402
9.3	28	10.27	2284	0.354	0.403



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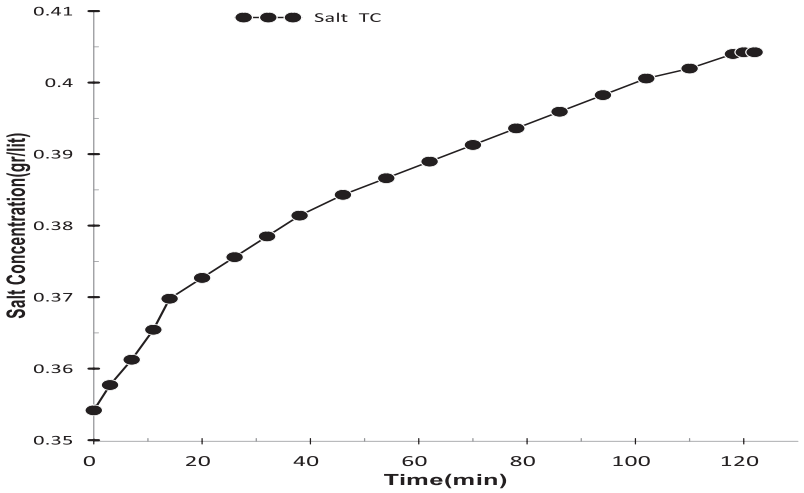

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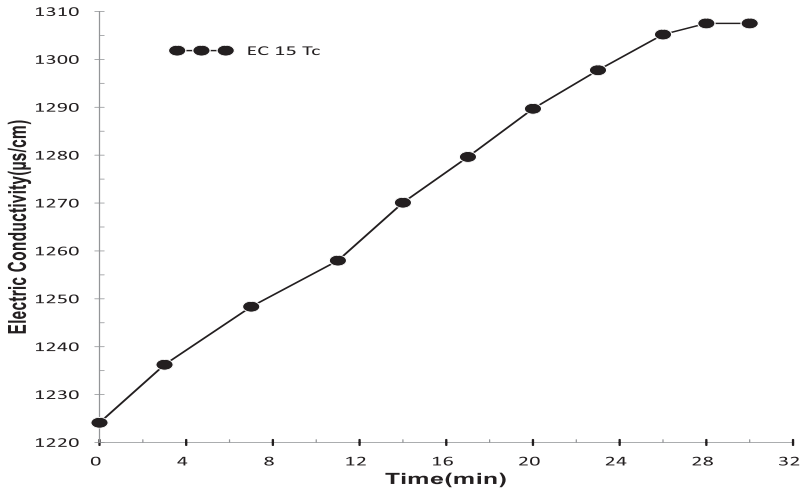
Fig. 6. Temperature difference=1.5 Celsius degree, Salt concentration=0.35 gr/liter (a)Electrical Conductivity(µs/cm) (b)Salt Concentration(gr/liter)



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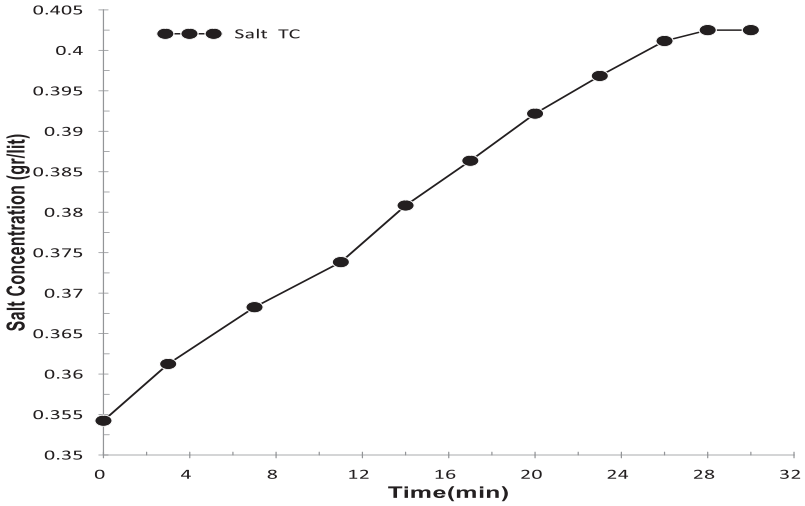

(b)

Fig. 7. Temperature difference=9.3 Celsius degree, Salt concentration=0.35 gr/liter (a)Electrical Conductivity(µs/cm) (b)Salt Concentration(gr/liter)

conductivity variation for the saline-water part is converged to zero, it can be deduced that the process is completed.

The RO desalination is dependent on three parameters. These parameters are pressure, temperature gradient, and salinity gradient. Without pressure gradient, temperature and salinity gradient are the two main factors for RO desalination. According to Table 4, it is observed when the temperature difference is 1.5 ^{o}C for different 1 and 0.35 g/l concentrations, electrical conductivity, water production and Process time are different. On the other hand, when the concentration is the same (1 g/l) and temperature differences are 1.5, 2.5, and 10.8^{o}C, electrical conductivity and water production are different. It is deduced that the temperature and the salinity gradients are effective in temperature-driven reverse osmosis.

Energy Comparison in SWRO and TDRO

Sea Water Reverse Osmosis (SWRO) desalination is a common desalination method in the world. This method needs a high-pressure pump. Because of using high-pressure

Table 8. Energy consumption comparison for SWRO and TDRO method

Energy consumption per Water production (kW/m^3)	
SWRO	5.63-7.93*
TDRO	2.26**

*According to different areas [22]

** For sea water condition, salt concentration=35 gr/lit and 1.934^o C temperature difference [20]

Table 9. Energy cost comparison between Electrical and solar energy [23]

	Electricity (US$/kW)	Solar Energy (US$/kW)
Installation Cost	220	3000-4000
Production Cost	0.174	0.06

Table 10. Advantages and disadvantages for SWRO and TDRO

Desalination method	Advantages	Disadvantages
SWRO	-Common and industrialized -More efficient to another common desalination method	-Need big equipment (like pumps, header and etc.) for a large unit -Energy consumption (5.63-7.93kW/m^3) -Maintenance costs
TDRO	-Energy consumption (2.26 kW/m^3) -Equipment requirement and sizing -Ability to use solar energy -Usable for remote area -Need to low maintenance	-In the research Phase

pumps, the equipment and maintenance costs are expensive. Also, the energy costs are high. In the temperature-driven reverse osmosis (TDRO) method, the energy and equipment costs are less than the reverse osmosis method. In this method, there is no need for a high-pressure pump. The comparison between SWRO and TDRO is summarized in Tables 8, 9, and 10.

It is necessary to mention; that manufacturing and operating the device on an industrial scale has its own challenges. It is not easy to create a certain temperature difference on both sides of the membrane on an industrial scale, especially, since more membranes are used on an industrial scale. The heat that leaves the system through the outgoing water also causes heat loss in the system. Therefore, the industrialization of the relevant process needs to do more research.

7- Conclusion

In the present study, the thermal gradient effect on the reverse osmosis process is conducted. In the absence of pressure-driven force, the effect of two factors on the reverse osmosis process is studied: 1: the temperature gradient between the permeate-water and the saline-water part and 2: the salt concentration of the saline-water part. In this work, at first, the experimental results are validated with Robinson et al.'s work. By considering the result, a good agreement is observed between experimental results and the reference. The maximum difference between experimental results and Robinson et al.'s results is 4.5%. The effect of different temperature gradients between the permeate-water and the saline-water part is studied. By considering the results, it can be concluded that rising the temperature gradient and salt

concentration, have a direct effect on process time, penetration rate, and saline-water part concentration. According to the results, it is observed that by increasing the temperature gradient and saline-water part concentration, the driving force for the process increases. According to this enhancement, the Process time decreases and pure water penetration from the saline-water to the permeate-water part increases. As a result, the variations of electrical conductivity and salt concentration on the saline-water part increase.

The required energy for water production by temperature-driven reverse osmosis is obtained and compared to the SWRO method. It can be concluded that the energy consumption for the TDRO method is about 40% of the SWRO method.

Acknowledgement

It is worth mentioning, that the experimental setup is supported through the Invention - Organization of Registration of Documents and Real Estate (Islamic Republic of Iran) under statement No.14015014000300165 2(05.27.2022).

Nomenclature

Abbreviations

EC	Electrical conductivity, µS/cm
l	liter
T	Temperature, Celsius degree

Subscripts

avg	Average
C	Saline-water part

References

[1] N. Lior, Advances in water desalination, A John Wiley & Sons, Inc., 2012.

[2] A. Alkaisi, R. Mossad, A. Sharifian-Barforoush, A Review of the Water Desalination Systems Integrated with Renewable Energy, Energy Procedia, 110(1876-6102) (2017) 268-274.

[3] E. Hameeteman, Future water (In)security: Facts, figures, and predictions, Global Water Institute, 2013.

[4] The United Nations world water development report 4: managing water under uncertainty and risk, executive summary, UNESCO World Water Assessment Program, 2012.

[5] C. Jacob, Seawater desalination: Boron removal by ion exchange technology, Desalination, 205(1-3) (2007) 47-52.

[6] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: Water sources, technology, and today's challenges, Water Research, 43(9) (2009) 2317-2348.

[7] W.J. Koros, R. Lively, Water and beyond: Expanding the spectrum of large-scale energy efficient separation processes, AIChE Journal, 58(9) (2012) 2624-2633.

[8] B. Belgasim, K. Mahkamov, Theoretical Modelling of a Dynamic Solar Thermal Desalination Unit with a Fluid Piston Engine, in, World Renewable Energy Congress, 2011.

[9] Desalination of Seawater (M61): AWWA Manual of Water Supply Practice, American Water Works Association, 2011.

[10] M. Mulder, Basic Principles of Membrane Technology, Springer Dordrecht, 1996.

[11] P. Geisler, W. Krumm, T.A. Peters, Energy consumption and recovery reverse osmosis, Desalination, 122 (1999) 151-156.

[12] C. Fritzmann, J. Lowenberg, T. Wintgens, T. Melin, State-of-the-art of reverse osmosis desalination Desalination, 216 (2007).

[13] N. Hilal, G.J. Kim, C. Somerfield, Boron removal from saline water: A comprehensive review, Desalination, 273 (2011) 23-35.

[14] J.H. Redondo, A new concept for two-pass SWRO at low O&M cost using the new high-flow FILMTEC SW30-380, Desalination, 138 (2001) 231-236.

[15] D. Rana, T. Matsuura, Surface modifications for antifouling membranes, Chemical Reviews, 110 (2010) 2448-2471.

[16] A. Abdelrasoul, H. Doan, A. Lohi, Materials and membrane technologies for water and energy sustainability, Sustainable Materials and technologies, 7 (2016) 1-28.

[17] M. Faigon, Success behind advanced SWRO desalination plant, Filtration+ Separation, 53 (2016) 29-31.

[18] R. Sheikholeslami, Strategies for future research and development in desalination–Challenges ahead, Desalination, 248 (2009) 218-224.

[19] B.V.d. Bruggen, P. Luis, Forward osmosis: understanding the hype, Reviews in Chemical Engineering Journal, 31 (2015) 1-12.

[20] J. Robinson, J. Meehan, A. Taqi, E. Binner, B. Tokay, Water desalination using a temperature gradient, Desalination, 464 (2019) 1-7.

[21] C.S. Lee, E. Binner, C. Winkworth-Smith, enhancing natural product extraction and mass transfer using selective microwave heating, Chemical Engineering. Scientific, 149 (2016) 97-103.

[22] Desalination Technologies and Economics: CAPEX, OPEX & Technological Game Changers to Come, Almar Water solution, CMI Marseille, France, 2016.

[23] fred.Stlouifed.org, U.S. Bureau of Labor Statistics

HOW TO CITE THIS ARTICLE
M. Zhyianey Bakhsh, E. Abedini , S. Niazi, P. Adibi, Y. Bakhshan, Experimental study of thermal gradient effect on reverse osmosis process, AUT J. Mech Eng., 8(2) (2024) 109-122.

DOI: 10.22060/ajme.2024.22913.6084