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Direct Contact Membrane Distillation for Desalination Brine Solution

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ABSTRACT

Desalination is a process where fresh water produces from high salinity solutions, many ways used for this purpose and one of the most important processes is membrane distillation (MD). Direct contact membrane distillation (DCMD) can be considered as the most prominent type from MD types according to ease of design and modus operandi. This work studies the efficiency of using DCMD operation for desalination brine with different concentration (1.75, 3.5, 5 wt. % NaCl). Frame and plate cell was used with flat sheet PTFE hydrophobic type membrane. The study proves that MD is an effective process for desalination brines with feed temperature less than 60°C especially for feed with low TDS. 37°C, 47°C, and 57°C was feed temperature and 17, 22, 27°C as permeate temperatures used in study, temperature in both sides of membrane are recorded and TDS for permeate collected to assure that there is no penetration of brine to permeate side, the results took every 30 min for time experiment of 180 min. From results, the flux increases with increasing feed temperature and flow rate, and decreasing with increasing feed concentration, experiment time, and permeate temperature.

Key Words: direct contact membrane distillation, desalination, NaCl solution, PTFE membrane.

التقطير بواسطة الأغشية بالاتصال المباشر كنظام لتحلية المياه المالحة

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الخلاصة

التحلية عبارة عن عملية انتاج مياه نقية من مياه عالية الملوحة، عدة طرق استخدمت لهذا الغرض وواحد من اهم الانواع هو التقطير بواسطة الاغشية. يعتبر التقطير بواسطة الاغشية بطريقة الاتصال المباشر من ابرز الانواع بالنسبة لطرق التقطير بالاغشية استنادا الى سهولة العمل والتصميم. العمل لحالي يدرس كفاءة استخدام طريقة التقطير بواسطة الاغشية بطريقة الاتصال المباشر لتحلية محلول ملحي مختلف التراكيز (1.75, 3.5, 5 نسبة مئوية من ملح NaCl). تم استخدام خلية الاطار واللوح كنموذج في التجربة وباستخدام ورقة مسطحة لغشاء طارد للمياه من نوع (PTFE). الدراسة اثبتت بان عملية التقطير بواسطة الاغشية فعالة لتحلية المياه في درجة حرارة لقيم اقل من 60 درجة مئوية خصوصا لمياه ذات كمية املاح ذائبة قليلة. 37, 47, 57 درجة مئوية تم استخدامها كدرجة حرارة لقيم فيما كانت درجة حرارة الماء المقطر 17, 22, 27 درجة مئوية. تم تسجيل درجة الحرارة على جانبي الغشاء وقيمة الاملاح الكلية الذائبة للماء المقطر

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لغرض التأكد من عدم نفاذ المياه المالحة خلال الغشاء, وكانت مدة كل تجربة 180 دقيقة يتم جمع النتائج كل 30 دقيقة. بينت النتائج ان كمية التدفق تزداد بزيادة درجة حرارة اللقيم ومعدل الجريان, بينما ينخفض التدفق بزيادة الوقت وتركيز اللقيم وارتفاع درجة حرارة الماء المقطر.
الكلمات المفتاحية: التقطير بواسطة الاغشية بالاتصال المباشر, التحلية, محلول ملح الطعام, غشاء من نوع PTFE.

1. INTRODUCTION

The decrease of water beside the global warming and shortage in ambushes and oil stocks could be considered as one of the most dangerous problems for the new millennium. On the other hand, the United Nations Millennium Development Goals, published in 2009, stated that more than 880 million people do not have enough amount of saving water; of these, less than 85% live outside cities, **DESA, 2009**. The evanescence of fresh water is a dreadful problem in most places in the world, for this reason, desalination had become one of the most important ways for fresh water production from brackish and saline water, **Sun, et al., 2014**. Desalination can be defined as a process which takes brine solution as feed to produce fresh water by isolating the fresh water from saline water which became saltier.

Many ways of desalination were used for freshwater production as employing membranes under isothermal conditions by using a driving force based on the differences in hydrostatic pressure (Nanofiltration (NF) and Reverse Osmosis (RO)), or electric potential (electrodialysis), or by using thermal conditions as in multi-stage flash distillation (MSF) and other ways. MSF and RO are the most commercial methods, **Ibrahim, et al., 2013**, these types take high energy according to their technique also they have many disadvantages such as generating bacteria and fouling (by-product), also because process high pressure resulting in the film polarization and the high power consumption, for, it is necessary to look for new techniques. One of the hybrid non-isothermal techniques is a membrane distillation (MD) used to reduce energy exhaustion, **Pangarkar, et al., 2011**. MD considered as one of the new processes and used when the water is the main component in feed solution, **Hou, et al., 2009**. MD is an uncouth process that can be adapted effectively for water desalination or water treatment in industrial applications, by recycling the wastewater, thus ensuring this water to get fresh water, **Alzahrani, et al. 2013**. MD is suitable for the small system as approved, **Qtaishat, et al., 2013**.

The driving force in MD is a difference in partial pressure, and the presence of a hydrophobic membrane assures high water quality without taking into account the feedstock properties. Hot side temperatures under boiling point are suitable; hence this process is ideal for investing waste heat or solar thermally resources, **Kullab, 2011**. Energy consumption is the main challenge in the MD technique, which affects on produced water cost. MD driving thermal force needs to modest temperature, which can be provided from non-traditional energy like solar energy or waste energy, **Al-Obaidani, 2008**. There are four main types of MD, **Alkhudhiri, et al., 2012**: direct-contact-membrane distillation (DCMD), sweeping-gas-membrane distillation (SGMD), air-gap-membrane distillation (AGMD), and vacuum-membrane distillation (VMD), these types took their name from the mechanism of the process. DCMD and AGMD are proper for implementation where permeating flux is water, while VMD and SGMD are suitable for separation of a volatile organic or dissolved gas from salty solution.

The advantage and disadvantage of MD are different from type to another. In general, the main advantages of MD are exploitation of waste energy or /and solar energy because the process occurred in relatively low temperature and low pressure, its simple design and the high efficiency of separation. The disadvantages of MD are heat loss by conduction, low flux



amount and temperature polarization effect, **Martinez, et al., 2001**. Indirect contact membrane distillation (DCMD) the membrane surfaces are in direct contact with two liquid phases, the feed (warm solution) and permeate (cold solution), where they are in different temperatures, **Cath, et al., 2004**. Only vapor transports across the membrane then condenses directly in a stream of cold distillate, this mechanism gives DCMD technology its name (direct contact). The vapor/liquid equilibrium establishes the separation mechanism, which means the highest permeation rate for the highest partial pressure, **Phungsai, 2013**.

The purpose of this work was to verify the efficiency of using membrane distillation as a desalination method for brine solution with temperatures of feed and permeate found environment a naturally to reduce energy.

2. EXPERIMENTAL WORK

2.1 Experiment System Contents

Plate and frame cell was used as the main element in the experimental set up of DCMD. A flat sheet of polytetrafluoroethylene (PTFE) membrane was instilled inside the cell with properties shown in **Table 1**, the system is shown in **Fig. 1**. Feed (hot) enter to the cell by a special pump (high-temperature resistance and non-corrosive) from glass tank with two-liter volume, the heater of 750 w is submerged inside the tank with a controller in order to obtain the heat required for feed. In the other side, the pump provides permeate (cold) liquid to the cell from a tank of two-liter volume, the cooling source provided by cool water coil submerged in the permeate tank with the controller to give the required temperature. The flux was measured by electronic sensitive balance (-600 to +600 gr). Four thermometers used to measure inlet temperature and the temperature inside the membrane model in both flow lines. Four pressure gauges are used to measure pressure at the inlet and outlet for both lines. Feed and permeate are controlled by valves (for measuring and adjusting flow) with two rotameter. **Table 2** showing the properties of the equipment used in the experiment.

2.2 Work Method

From **Fig. 1**, the feed (brine solution) was inside and permeate in another side of the system and the membrane located between them. The vapor of flux transported through the membrane from the feed side to permeate side where accumulated and measured.

2.3 Feed and Permeate Solutions Properties

NaCl salt is used to make the brine solution with different concentration of 1.75, 3.5, 5 wt. % NaCl. NaCl salt has the properties showing in **Table 3**. Permeate solution was distilled water prepared from one step laboratory distillation device; the distilled water has the specific properties listed in **Table 4**.

2.4 The Measured Parameters

Results measured every 30 min, with 180 min as operating time. The parameters were flux, TDS for permeate side, inlet and outlet pressure for permeate and feed line, the temperature at feed and permeate tank, temperature before entering the cell for permeate and feed, and the temperature inside the cell for both sides of the membrane. At all-time of experiment random TDS test done for permeate to be sure there is no penetration for feed solution through the membrane.



2.5 Operating Conditions

37, 47, and 57°C were feed temperatures (T_F), and 17, 22, 27°C used as permeate temperatures (T_P), feed flow rate (Q_F) was 50 l/h with increasing and decreasing 20 l/h, and permeate flow rate (Q_P) was 40 l/h, with co-current flow, the pressure in feed side less than 0.05 bar and in permeate side almost atmospheric pressure. Operation conditions were kept to be constant at all experiment time

3. RESULTS AND DISCUSSION

3.1 Effect of Time

Experimental results showed that with the passage of time there is an irregular decrease in flux amount in all concentrations, this decrease interspersed with significant increase in flux. This decrease in efficiency was caused by fouling and scaling, this decrease is less than other membrane (RO) separation process because of the difference of pore size in these types of membrane, and this behavior agreement with, **Kullab, 2011**. Fouling and scaling lead to clogging in the membrane pore, also they cause to damage or wetting membrane, fouling is caused by deposition of salts particles which they are depend on size of solids. When concentration increases, there is a significant decrease in flux. This behavior match with, **Martínez, 2004 and Martínez, et al., 1999**, and it is due to decreasing in vapor pressure. **Fig. 2** shows the effect of time on flux for feed of 3.5 wt. % NaCl with selected operational conditions, flux decrease from 9.43 LMH at first half hour of experiment to 7.07 LMH at end of experiment (after 180 min) with a decrease of 25%.

3.2 Effect of Feed Concentration

Feed concentration has a significant impact on flux. With increasing in feed concentration flux decrease due to a decrease in vapor pressure according to concentration polarization which effects on energy efficiency, **Alkhudhiri, et al., 2012**. The decrease in flux with increase concentration results in decreasing water activity coefficient, decrease in mass transfer coefficient and decrease in heat transfer coefficient, **Lawson, et al., 1997**. **Fig. 2** shows the effect of feed concentration on flux with the same operating conditions used for time effect. The flux was decreased slightly from 10.41 LMH for a feed of 1.75 wt. % NaCl to 9.43 LMH for a feed of 3.5 wt. % NaCl at first half hour with decreasing of 9.4%, and from 7.61 LMH to 7.07 LMH at 180 min of experiment time with decreasing of 7.1 LMH. The decrease in flux was highly different when the concentration of feed was 5 wt. % NaCl with a decrease of 2.99 LMH at first half hour and 2.44 LMH after 180min of experiment time. This behavior is in agreement with **Samraa, 2014**.

3.3 Effect of Feed Temperature

The flux increased with increasing feed temperature, and it's greatly affected by feed temperature. As in all MD types the driving force is vapor pressure, which vary with feed stream temperature, **Zhang, et al., 2010**. This increasing also depends on the increasing of diffusion of the penetrate molecules of membrane, which is caused by increasing in thermal motion of membrane polymer chain, and the increasing in temperature make permeate molecules more active and easy to diffuses according to the Eyring theory of diffusion **Aoran, et al., 2016**. Increasing feed temperature can be used as one of fouling problem solutions, and increasing in feed temperature make heat flow more effective, this because of increasing membrane temperature, which lead to increasing in the thermal conductivity of the



membrane. This is in agreement with, **Cheng, et al., 2010. Fig. 3** showing the effect of feed temperature on flux, at first half hour of experiment the flux increased for feed of 3.5 wt. % NaCl from 6.66 LMH for feed temperature of 40°C to 9.43 LMH for feed temperature of 47°C with increasing of 29.4%, and this flux increase to 12.24 LMH for feed temperature of 57°C with increasing in the flux by 23%. For the time of 180 min of the experiment the flux increasing for the same temperatures respectively was from 4.77 LMH to 7.07 LMH then to 7.02 LMH with increasing of the flux of 32.5% and 10.7%. This behavior is agreeing with, **Khaled, et al., 2016.**

3.4 Effect of Permeate Temperature

With increasing in permeate temperature there is a decrease in flux according to decrease in vapor pressure due to decrease in temperature difference between hot and cold side of membrane. In **Fig. 4** the flux decreased at first half hour of experiment from 7.34 LMH to 4.41 LMH then to 3.37 LMH when permeate temperature increased from 17°C to 22°C then 27°C respectively with a decrease of 40% and 23.6%, for the final results (after 180min) of experiment the flux decrease for the same permeate temperature from 5.05 LMH to 3.4 LMH then to 1.66 LMH with a decrease of 32.7% and 51.2% for every increasing in permeate temperature, this result agreed with, **Kayvani, 2013.** With comparison between increasing the feed temperature or decreasing permeate temperature for same concentration it's manifested that: to increase the flux amount it is favor to increase feed temperature than decrease permeate temperature because with rising feed temperature fouling and scaling decrease and its one of the ways of decreasing fouling, also practically increasing feed temperature is more easier than decreasing permeate temperature.

3.5 Effect of Feed Flow Rate

Feed flow rate has a relation with feed velocity, with the increase in velocity flux increase. Velocity increases convective heat transfer which decreases temperature polarization and thermal boundary layer thickness which in turn leads to increase in flux. Increasing in feed flow rate leads to turbulent flow which makes temperature at interface nearby to bulk temperature. Increasing feed flow rate leads to decrease in temperature and concentration polarization which leads to increase in flux, with increasing the feed flow rate the fouling decreased which lead to increase in flux, so the increase in feed flow rate can be considered as one of the solutions for fouling and scaling problems. **Fig. 5** shows the effect of increasing and decreasing feed flow rate, the experimental results recorded for the same increasing and decreasing feed flow rate of 20 l/h. With increasing feed flow rate at constant permeate flow, there is slightly increasing in the flux from 9.43 LMH at feed flow rate of 50 l/h to 9.97 LMH for 70 l/h feed flow rate, with 5.4% increase in flux at first half hour of the experiment. When decreasing the flow rate from 50 l/h to 30 l/h, flux decreased from 9.43 LMH to 9.12 LMH, with decreasing of 3.3% at first half hour. This behavior is in agreement with, **Martinez, et al., 2001.**

3.6 Permeate TDS Results

In every experiment TDS was measured analytically to calculate the process efficiency, also there is random measurement for permeate TDS during the experiment to assure that there is no penetration of feed through the membrane to permeate side. The results showed that DCMD has high efficiency with 99.99% because there is no change in TDS results to permeate in all experiment time.



4. CONCLUSIONS

1. With increasing in time flux in all feed concentrations and all feed and permeate temperatures decreased .
2. With increasing feed concentration flux for all feed and permeate temperatures decreased.
3. With increasing feed temperature flux increased for all feed concentrations.
4. With increasing permeate temperature flux decrease for all feed concentrations and temperatures.
5. With increasing feed flow rate flux increased.
6. The DCMD process showed high efficiency reached to 99.99%.

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NOMENCLATURE

Q_F = feed flow rate, l/h
 Q_P = permeate flow rate, l/h
TDS= total dissolved solids, mg/l
 T_F = feed temperature, °C
 T_P = permeate temperature, °C

ABBREVIATIONS

LMH= liter per square meter per hour
NF= nanofiltration
RO= reverse osmosis
MSF= multi-stage flash distillation
PTFE= polytetrafluoroethylene
PP= Polypropylene
MD= membrane distillation
DCMD= direct contact membrane distillation

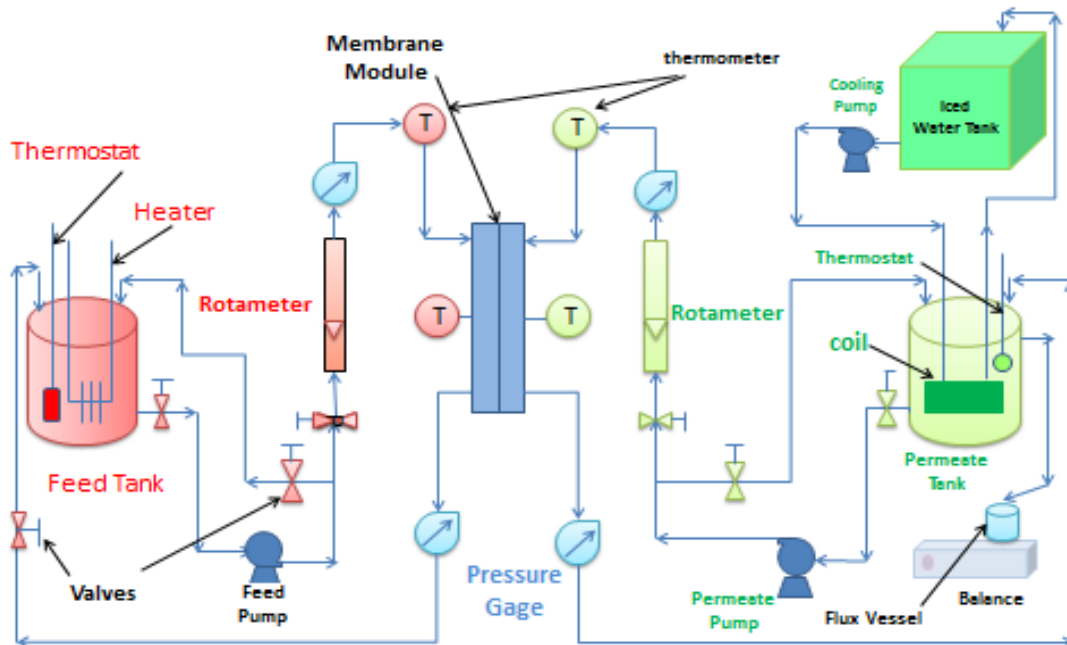


Figure 1. DCMD Schematic Diagram.

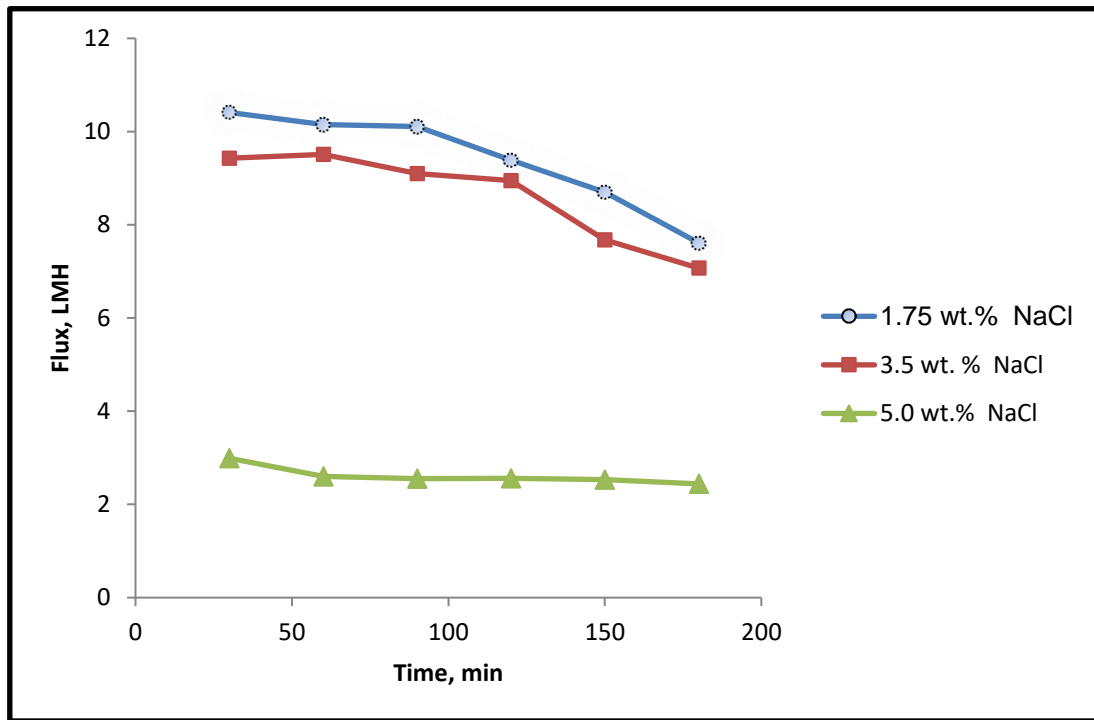


Figure 2. Effect of concentration on flux amount ($Q_F=50$ l/h, $Q_P=40$ l/h, $T_F=47$, $T_P=17^\circ\text{C}$).

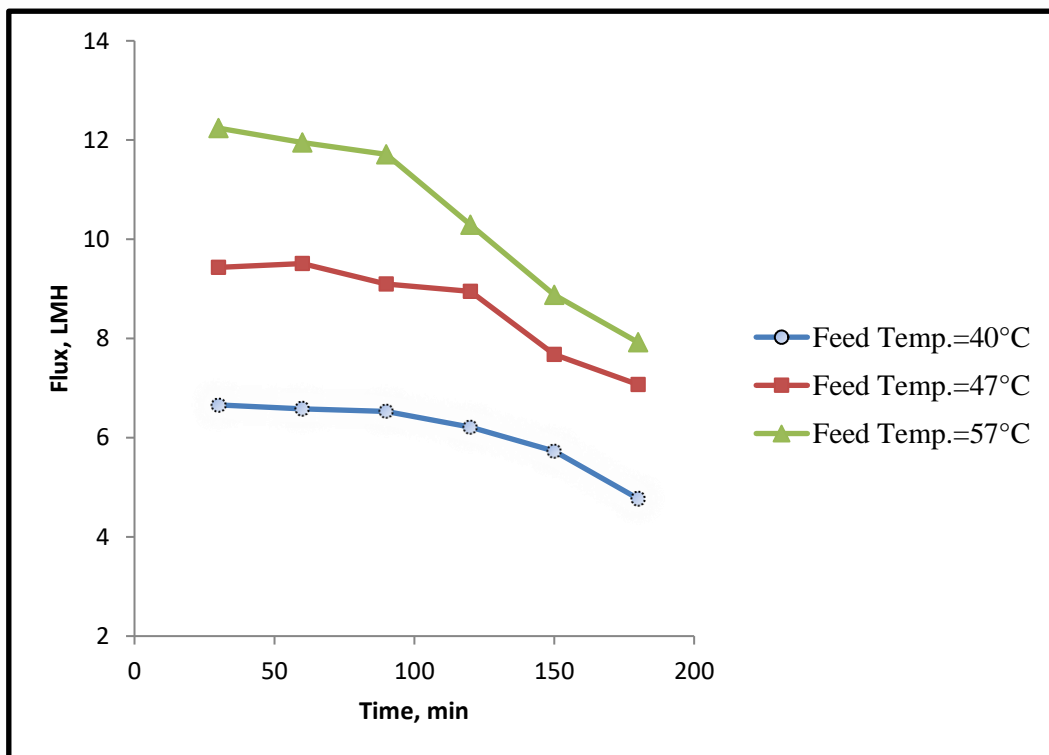


Figure 3. Effect of feed temperature on flux amount ($Q_F=50$ l/h, $Q_C=40$ l/h, $C_F= 3.5$ wt. %NaCl, $T_P=17^\circ\text{C}$).

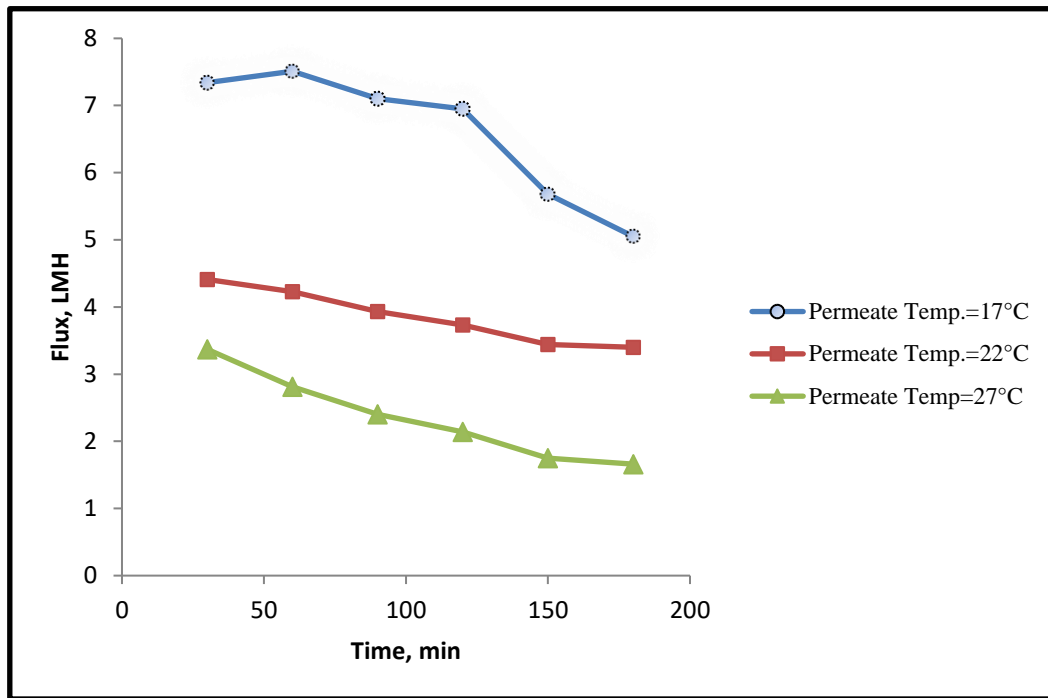


Figure 4. Effect of permeate temperature on flux ($Q_F=50$ l/h, $Q_P=40$ l/h, $C_F= 3.5$ wt. % NaCl, $T_F=47^\circ\text{C}$).

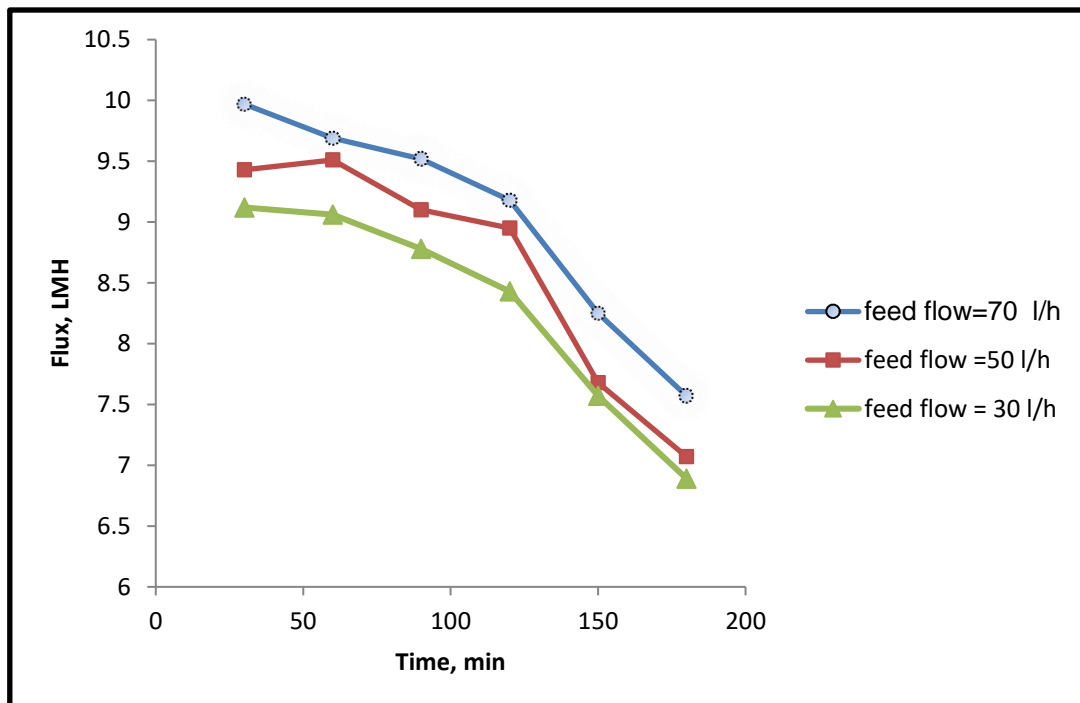


Figure 5. Effect of Feed Flow Rate on Flux ($Q_P=40$ l/h, $C_F= 3.5$ wt. % NaCl, $T_F=47^\circ\text{C}$, $T_P=17^\circ\text{C}$).



Table 1. PTFE membrane properties.

Parameter	Value mg/l
ePTFE substrate (QMO385) thickness	nominally rated at 25.4-50.8µm via ASTM D1777
Polypropylene non-woven substrate thickness:	nominally rated at 76.2-177.6µm
Total thickness (PP + PTFE)	nominally rated at 127-203 micron
Liquid Water Entry Pressure	> 50psi, via ASTM D751
Void volume	> 90%
Pore size	0.2 µm
Operation temperature	232°C
Air permeability:	0.1-0.4 ft ³ ft ⁻² min ⁻¹ at 125pa (13-40 l cm ⁻² h ⁻¹ at 0.07 bar)
Manufacture	Sterlitech Company-Kent-USA

Table 2. Equipment properties.

Equipment	Origin	Properties
Feed pump	Germany/ Grundfos	Type UPS 25-60, max. pressure =10 bar, liquid temp.= +2°C to 110°C, max. flow =4.65 m ³ /h
Permeate and cooling pump	Taiwan/ Water Quality Association	50 G Grand Forest type, inlet pressure= 29 PSI, open flow= 1 LPM
Feed heater	China	Power= 750 W, voltage= 220V
Thermostat	China	Range= -50°C to 70°C
Rotameter	Germany	Range= 25 to 250l/h
Thermometer	China	Range= -50°C to 70°C
Pressure Gage	China	Range= -1 to 1 bar



Table 3. NaCl salt properties.

Item	Specification
Company	Edutek Chemicals/India
Assay (ex Cl)	99.5% min
Loss on drying at 1050°C	1.0%
Sulphate (SO ₄)	0.02%
Ammonia (NH ₃)	0.002%
Iron (Fe)	0.002%
Lead (Pb)	0.0005%
Potassium (K)	0.02%

Table 4. Distilled water properties.

Parameter	Value mg/l
TDS (analytically)	21
Sodium	Zero
Potassium	Zero
Total Hardness	39.6
Chloride	1.03
Alkalinity	8
Magnesium	5.98
Calcium	6.03
SO ₄	1.23
pH	6.5