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# A Study of Forward Osmosis Using Various Drawing Agents

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## Abstract

*This research was aimed to study the osmotic efficiency of the draw solutions and the factors affecting the performance of forward osmosis process. The draw solutions used were magnesium sulfate hydrate (MgSO4.7H2O), potassium chloride (KCl), calcium chloride (CaCl2), and ammonium bicarbonate (NH4HCO3). It was found that water flux increases with increasing draw solution concentration, and feed solution flow rate and decreases with increasing draw solution flow rate and feed solution concentration. And also found that the efficiency of the draw solutions is in the following order:*

$CaCl_2 > KCl > NH_4HCO_3 > MgSO_4.7H_2O$

***Keywords***: Forward Osmosis, Draw solution, Desalination

## Introduction

Desalination refers to the wide range of processes designed to remove salts from waters of different qualities Desalination technology is in use throughout the world for a wide range of purposes, including providing potable fresh water for domestic and municipal purposes, treated water for industrial processes, and emergency water for refugees or military operations Because of growing concerns about water scarcity and quality, and disputes over allocations of scarce water resources, a tremendous amount of effort has been devoted to developing technologies to desalinate the vast quantities of seawater available [1].

To reduce the cost of existing desalination technologies, it is prudent to focus on what makes current technologies so expensive. Energy is indisputably the most significant contributor to the cost of desalination. Hence, reduction in energy usage is the primary objective to making desalination more affordable [2].

Forward (or direct) osmosis (FO) is a process that may be able to desalinate saline water sources at a notably reduced cost. In forward osmosis, like RO, water transports across a semi-permeable membrane that is impermeable to salt. However, instead of using hydraulic pressure to create the driving force for water transport through the membrane, the FO process utilizes an osmotic pressure gradient. A "draw" solution having a significantly higher osmotic pressure than the saline feed water flows along the permeate side of the membrane, and water naturally transports across the membrane by osmosis. Osmotic driving forces in FO can be significantly greater than hydraulic driving forces in RO, potentially leading to higher water flux rates and recoveries. The lack of hydraulic pressure may make the process less expensive than RO, while the minimization of brine discharge reduces the environmental impact of the desalination process [3].

**Previous forward osmosis efforts**

In 1965, Batchelder [4] described a process of adding volatile solutes, such as sulfur dioxide, to seawater or freshwater to create a solution which may be used in a forward osmotic process to extract water from seawater. The suggested membrane to be used in this process was cellulosic in nature. Other examples in the patent described the use of carrot root as a membrane material. The process is carried out until the draw solution is sufficiently dilute, at which point the volatile solute is removed by heating and/or air stripping.

In 1972, Frank [5] described a method of forward osmosis using a precipitable salt, in this case aluminum sulfate, as the draw solution solute. Following osmosis of water across the membrane, the diluted draw solution was dosed with calcium hydroxide, leading to the precipitation of aluminum hydroxide and calcium sulfate. The precipitate is removed by standard methods leaving the fresh product water. Excess calcium hydroxide from the precipitation step can be removed by dosing with sulfuric acid or carbon dioxide, which produces calcium sulfate and calcium carbonate precipitates, respectively. This step required additional solid removal and led to neutral pH in the product water. The membrane used in the patent was cellulose acetate membrane.

In 1975, Kravath and Davis [6] described a process of seawater desalination achieved by forward osmosis of water across a cellulose acetate membrane. Initial tests were run with a dialysis cell with glucose as the draw solute and seawater as the feed. Additional tests were run with glucose dissolved in seawater as a draw solution. Emergency lifeboats were considered as a possible use of the process in which seawater was brought aboard a lifeboat and glucose was added. Additional seawater was passed through a dialysis unit leading to osmosis and a dilution of the seawater/ glucose draw solution. Upon dilution, the salinity was reduced to a level where ingestion was possible for short term consumption. The flat sheet cellulose acetate membranes did not perform well in terms salt rejection. Hollow fiber membranes were also tried and results improved. Draw solute removal was not considered because the solute was intended for ingestion.

In 1994 Herron [7] were awarded a patent on a membrane module and a method to concentrate fruit juices and wines. In the summary of the invention, the inventors recommended the use of 50–85 wt. % sugar solution as the draw solution.

In 2002, McGinnis [8] described a method of forward osmosis using a combination of draw solutions across several semi-permeable membranes. This patent combined the ideas of draw solution recycle with an osmotically efficient draw solution to increase recovery. The two-stage FO process takes advantage of the temperature dependent solubilities of the solutes, in this case potassium nitrate (KNO3) and sulfur dioxide (SO2). Seawater was heated and fed to the FO membrane unit where a heated solution of saturated potassium nitrate served as the draw solution. The diluted draw solution was sent to a new chamber where it was cooled by incoming seawater, which was simultaneously heated to the appropriate feed temperature. Upon cooling, a significant portion of the KNO3 precipitates out of solution, reducing the osmotic pressure. Next, the diluted KNO3 solution is drawn to another FO unit, where dissolved SO2 acted as the draw solution. The dilute KNO3 solution had a low osmotic pressure in comparison with the saturated SO2 solution, and water diffused across the membrane while the KNO3 was rejected. The sulfur dioxide was then removed through standard means, leaving potable water. All solutes were recycled in the process.

In 2005 Jeffrey [2] described a forward osmosis process for seawater and brackish water desalination. The process used ammonium bicarbonate draw solution to extract water from saline feed water across a semi-permeable polymeric membrane. Very large osmotic pressures generated by the highly soluble ammonium bicarbonate draw solution yield high water fluxes and could result in very high feed water recoveries. Upon moderate heating, ammonium bicarbonate decomposed into ammonia and carbon dioxide gases that could be separated and recycled as draw solutes, leaving the fresh product water. Experiments with a laboratory-scale FO unit utilizing a flat sheet cellulose tri-acetate membrane demonstrated high product water flux and relatively high salt rejection.

In 2009, a novel osmotic membrane bioreactor (OsMBR) is presented by Andrea [9]. The system utilizes a submerged forward osmosis (FO) membrane module inside a bioreactor. Through osmosis, water is transported from the mixed liquor across a semi-permeable membrane, and into a draw solution (DS) with a higher osmotic pressure. To produce potable water, the diluted DS is treated in a reverse osmosis (RO) unit; the by-product is a reconcentrated DS for reuse in the FO process. Membrane fouling was controlled with osmotic backwashing. The FO membrane was found to reject 98% of organic carbon and 90% of ammonium-nitrogen; the OsMBR process (bioreactor and FO membrane) was found to remove greater than 99% of organic carbon and 98% of ammonium-nitrogen, respectively; suggesting a better compatibility of the OsMBR with downstream RO systems than conventional membrane bioreactors.

**The ideal drawing agent for forward osmosis**

The drawing agents must have a high osmotic efficiency, namely high solubility in water and relatively low molecular weight, which can lead to high osmotic pressures [2].

Regardless of the application, osmotic agents should ideally be inert, stable, of neutral or near neutral pH, and non-toxic. They should not degrade the membrane chemically (through reaction, dissolution, or adsorption) or physically (fouling) and should have minimal effects on the environment or human health. They should also be inexpensive, very soluble, and provide a high osmotic pressure. For specific applications, additional criteria will apply, e.g. in desalination concept requires the drawing agent to be easily (both from a physical and energetic standpoint) and completely recoverable from water [10].

## Experimental Work

Figures 1 and 2 describes the apparatus used in laboratory-scale FO experiments

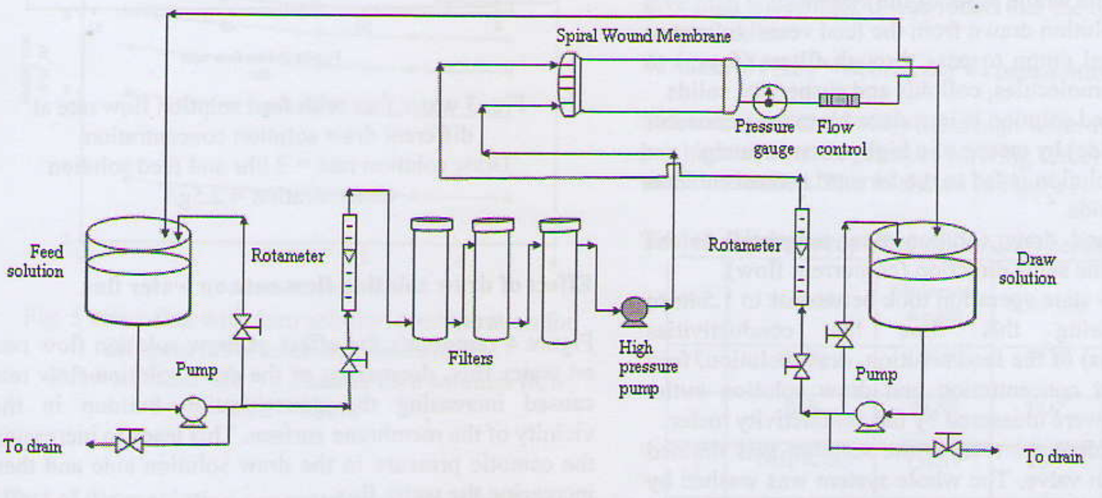


Fig. 1 Schematic Diagram of spiral wound forward osmosis Process

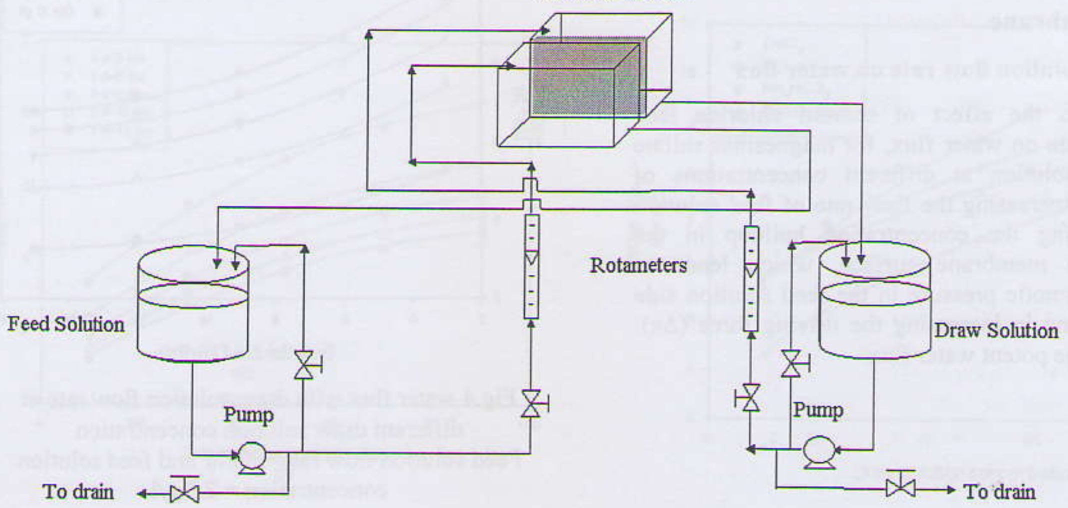


Fig. 2 Schematic Diagram of flat sheet forward osmosis Process

The Experimental work consists of two parts. The first part is to show the effect of operating conditions on the water flux in the TFC-HR membrane constructed as spiral wound module and the second part is to show the efficiency of different draw solutions in TFC-ULP membrane constructed as flat sheet module [11].

**The Experimental Procedure is**

a- Draw and feed solutions were prepared in the QVF glass vessels by dissolving the solid salt in 25 liter of deionized water.

b- The outlet valve of the feed vessels was open to let the solutions fill the whole pipes of the system.

c- The feed solution drawn from the feed vessel by means of a centrifugal pump to pass through filters (5 μm) to remove macromolecules, colloids and suspended solids

d- Then the feed solution is introduced into the permeator (on the feed side) by means of a high pressure pump

e- The draw solution is fed to the forward osmosis unit on the permeate side.

f- The feed and draw solution flow tangential to the membrane in the same direction (co-current flow).

g-The steady – state operation took between 1 to 1.5 hr to achieve. During this time the conductivities (concentrations) of the feed solution, draw solution, feed solution outlet concentration and draw solution outlet concentration were measured by the conductivity meter.

h- After recording the results, the solution was drained through a drain valve. The whole system was washed by deionized water. Now, the system is ready for the next run.

## Results and Discussion

### TFC-HR membrane

**Effect of feed solution flow rate on water flux**

Figure 3 shows the effect of sodium chloride feed solution flow rate on water flux, for magnesium sulfate hydrate draw solution at different concentrations of MgSO4.7H2O. Increasing the flow rate of feed solution caused decreasing the concentration buildup in the vicinity of the membrane surface, which leads to decreasing in osmotic pressure in the feed solution side and then resulting in increasing the driving force ($\Delta\pi$). I.e. increasing the potent water flux

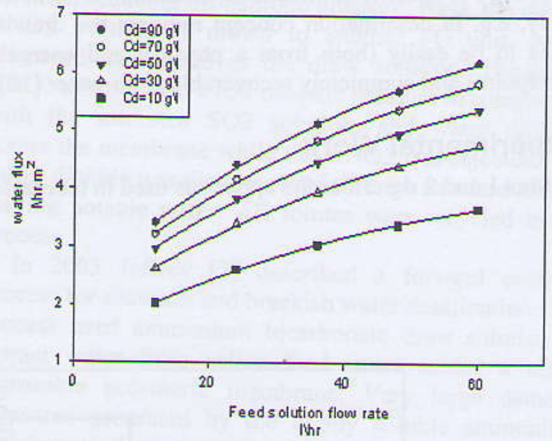


Fig. 3 water flux with feed solution flow rate at different draw solution concentration
Draw solution rate = 3 l/hr and feed solution concentration = 2.5g/l

**Effect of draw solution flow rate on water flux**

Figure 4 represents the effect of draw solution flow rate on water flux, decreasing of the draw solution flow rate caused increasing the concentration buildup in the vicinity of the membrane surface. This leads to increasing the osmotic pressure in the draw solution side and then increasing the water flux.

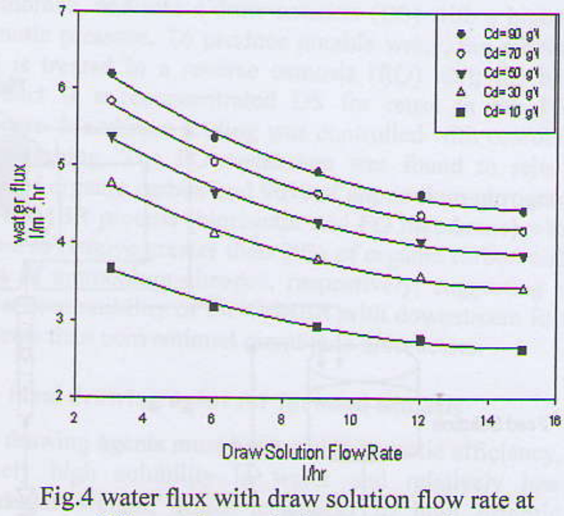


Fig.4 water flux with draw solution flow rate at different draw solution concentration
Feed solution flow rate=60l/hr and feed solution concentration = 2.5 g/l

### Effect of feed solution concentration on water flux

Figure 5 illustrate the effect of feed solution concentration on water flux, increasing the feed solution concentration leads to decreasing the driving force and then decreasing the water flux as shown in figure 5.

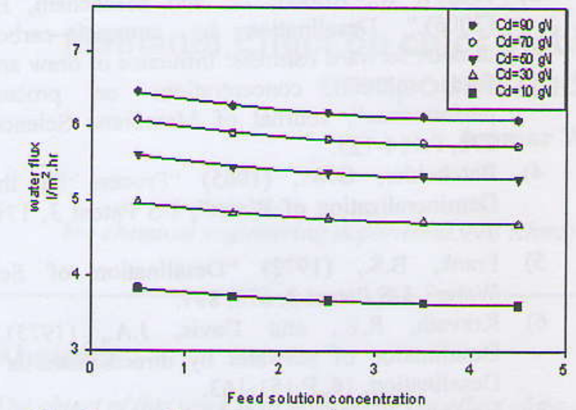


Fig. 5 water flux with feed solution concentration for different draw solution concentration
Draw solution rate = 3 l/hr and feed solution flow rate = 60l/hr

### Effect of draw solution concentration on water flux

Increasing the draw solution concentration will increase the driving force ($\Delta\pi$) and then increasing the water flux, this is shown in figure 6.

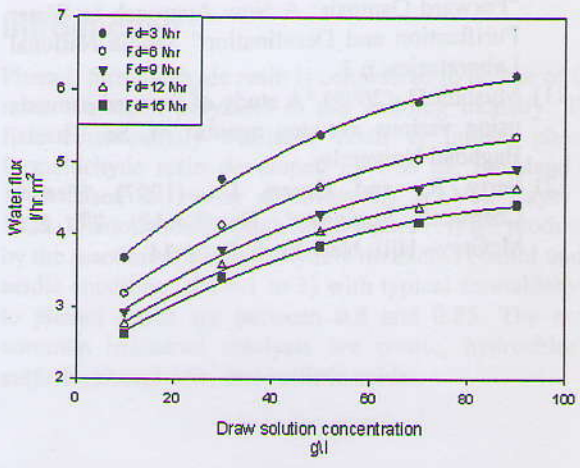


Fig.6 water flux with draw solution concentration at different draw solution flow rates
Feed solution flow rate = 60l/hr and feed solution concentration = 2.5 g/l

## TFC-ULP membrane

### Effect of the Type of Draw Solution

The draw solution solute must have high osmotic efficiency, meaning that it has to be highly soluble in water and have a low molecular weight in order to generate a high osmotic pressure. Higher osmotic pressure leads to higher water flux and feed water recovery.

Using different types of draw solutions in order to find the best one which has the highest osmotic pressure to give high water flux, it was found that the order of higher water flux is:

$J_{w\,(CaCl2)} > J_{w\,(KCl)} > J_{w\,(NH4HCO3)} > J_{w\,(MgSO4.7H2O)}$

Calcium chloride ($CaCl_2$) has a high water flux because it has highest osmotic pressure (driving force) than other material studied. This is shown in figure 7.

Table1 physical properties of the draw solution solute

| No. | Material | Molecular weight | Solubility | Osmotic pressure(bar)at $25^0$C&90 g\l |
|---|---|---|---|---|
| 1 | $CaCl_2$ | 110.99 | $59.5^{0°}$ | 69.747 |
| 2 | KCl | 74.56 | $27.6^{0°}$ | 53.907 |
| 3 | $NH_4HCO_3$ | 157.11 | $25^{15°}$ | 43.846 |
| 4 | $MgSO_4 \cdot 7H_2O$ | 246.49 | $72.4^{0°}$ | 10.159 |

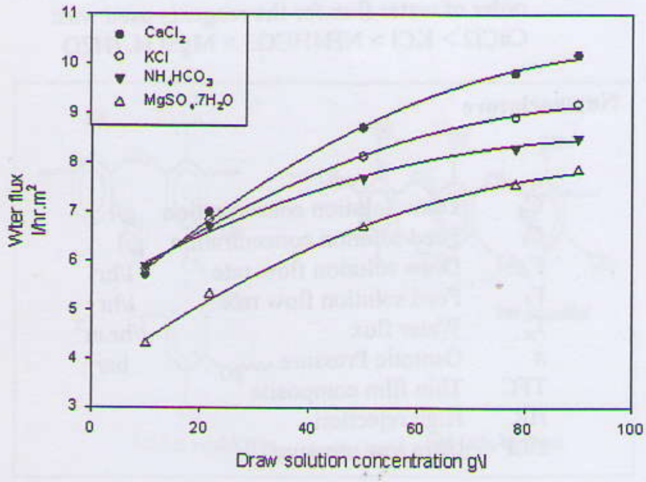


Fig.7 water flux with draw solution concentration for different draw solutions
Draw solution rate = 3 l/hr and, solution flow rate = 60l/hr and feed solution concentration = 2.5 g/l

## Conclusions

The following conclusions could be drawn from the present research [11]:

1- Forward osmosis can be used to separate water from a concentrated stream (e.g. saline water) that contains water and salt where the water transfer from low concentration (feed solution) to high concentration (draw solution)

2- The water flux produced from the osmosis cell increases by increasing the concentration of draw solutions and increasing the flow rate of feed solution and decreases by increasing the concentration of feed solution and increasing the flow rate of draw solutions. Some results for $MgSO_4.7H_2O$ in spiral wound module are given in the following table.

| $C_f$ | $F_f$ | $C_d$ | $F_d$ | $J_w$ |
|---|---|---|---|---|
| 0.5 | 60 | 90 | 3 | 6.461 |
| 4.5 | 60 | 90 | 3 | 6.089 |
| 0.5 | 12 | 90 | 3 | 3.562 |
| 0.5 | 60 | 10 | 3 | 3.838 |
| 0.5 | 60 | 90 | 15 | 4.623 |

3- Spiral-wound membrane which is normally used in reverse osmosis process can be modified and applied as a good alternative in direct osmosis process.

4- The best draw solution was the solution that gives higher water flux. It was found that the order of water flux for the reagents used was: CaCl2 > KCl > NH4HCO3 > MgSO4.7H2O

### Nomenclature

| | | |
|---|---|---|
| $C_d$ | Draw solution concentration | g/l |
| $C_f$ | Feed solution concentration | g/l |
| $F_d$ | Draw solution flow rate | l/hr |
| $F_f$ | Feed solution flow rate | l/hr |
| $J_w$ | Water flux | $l/hr.m^2$ |
| $\pi$ | Osmotic Pressure | bar |
| TFC | Thin film composite | |
| HR | High rejection | |
| ULP | Ultra low pressure | |

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