# FORWARD OSMOSIS PROCESS FOR CLEAN WATER PRODUCTION USING MAGNESIUM SULFATE

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## SUMMARY OF PROJECT

Currently, the reverse osmosis process (RO) is used in seawater desalination. It is an effective method for water recovery but requires a large amount of hydraulic energy. Forward osmosis (FO) process, a novel membrane technology, relies on the concentration difference between two solutions as a driving force for the transport of water across a semi-permeable membrane. It is a potentially more energy saving and efficient alternative than RO. Thus, our project focuses on finding a suitable FO draw solute to increase the rate at which water flows across the FO membrane to maximize the amount of clean product water obtained.

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## ABSTRACT

The forward osmosis (FO) process is being actively studied by various researchers as an alternative membrane technology for water reclamation due to its low energy requirement, high water recovery and high solute rejection. The main objective for this project is to investigate the feasibility of using magnesium sulfate ($MgSO_4$) as the solute for the draw solution in the FO process. A laboratory-scale FO cell set up was used for the measurement of water flux produced by using different draw solutes. $MgSO_4$ was compared with other draw solutes and observed to be the most suitable draw solute with a relatively high osmotic pressure and correspondingly high water flux. It was also discovered that FO membrane in the normal mode can produce a higher water flux than in the reverse mode. Compared to the other draw solutes, $MgSO_4$ can be easily removed via nanofiltration (NF) process to produce clean water and $MgSO_4$ can be regenerated as the draw solute. The FO process is comparable to the reverse osmosis (RO) process in terms of water flux and it utilizes a significantly lower amount of energy. Additional improvements can be made to the FO membrane structure to further increase the water flux.

## BACKGROUND AND PURPOSE OF RESEARCH AREA

Membrane processes, particularly reverse osmosis (RO) is currently one of the most successful technology for water reclamation and seawater desalination. However, with the increasing cost of energy, further reduction in energy consumption is desirable. Recently, the forward osmosis (FO) process is being actively studied by various researchers as an alternative membrane technology for water reclamation due to its low energy requirement, high water recovery and high solute rejection.

The FO process requires a draw solution that has a higher osmotic pressure than the feed solution. It utilizes an osmotic pressure gradient across a highly-selective membrane, such that only water can permeate from the feed solution through the membrane via osmosis to the draw solution. Various draw solutions at high concentration can have exceedingly large osmotic pressure, which may potentially lead to a much higher water flux and recoveries as compared to the more energy-intensive RO which utilizes hydraulic pressure.

The experimental set-up below as depicted in Figure 1 desalinates sea water (feed solution) to clean product water. The set-up consists of a FO module and a nanofiltration (NF) module. The water molecules from the feed solution pass through the membrane via osmosis into the draw solution due to the difference in osmotic pressure of the two solutions, while the salt in the feed solution is retained. Draw solutes which have high osmotic pressure can be used in the draw solution. Subsequent to the FO module is the NF module that is used to re-concentrate the diluted draw solution which will be reused as the concentrated draw solution for the FO module. At the same time, the NF module, which makes use of hydraulic pressure (less than 10% of the pumping energy used in RO), is capable of rejecting more than 98% of many different draw solutes to produce clean product water for human consumption and other usages.

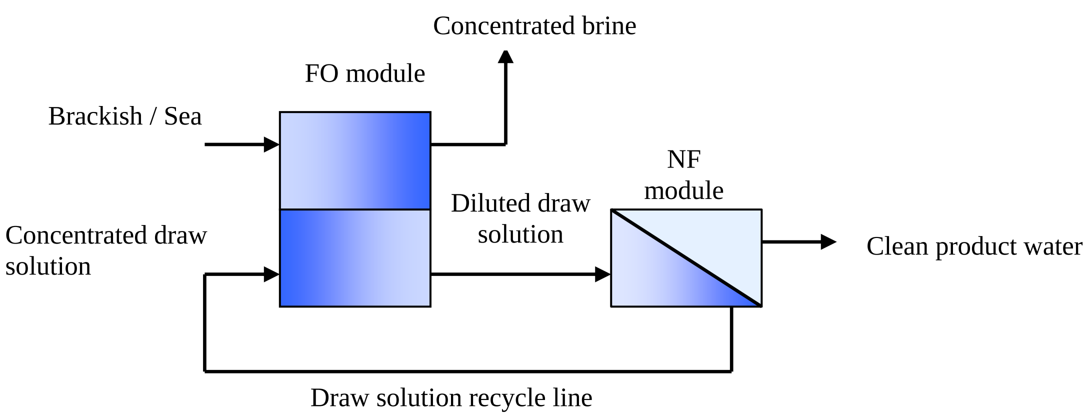


*Figure 1: Schematic diagram of the FO and NF process (software: Microsoft Word 2003)*

The main objective for this project is to investigate the feasibility of using magnesium sulfate as the solute for the draw solution in the FO process. By comparing magnesium sulfate with other solutes like glucose, fructose, magnesium chloride, calcium chloride and potassium chloride in terms of water flux, we can determine if magnesium sulfate is the most appropriate choice. An ideal draw solute must be able to produce a reasonably high water flux and can be easily removed from the draw solution via NF.

## HYPOTHESIS OF RESEARCH

It is hypothesized that among the draw solution investigated in this study, magnesium sulfate solution is an ideal draw solution for the FO process. It is predicted that $MgSO_4$ will generate a high osmotic pressure due to its relatively high solubility in water as compared to the other solutes investigated in this study. Magnesium and sulfate ions are comparatively larger in ionic size than the other solutes; hence, $MgSO_4$ molecules can be easily removed via NF for the regeneration of the MgSO4 draw solution and concurrently producing the clean product water.

## MATERIALS AND METHODS

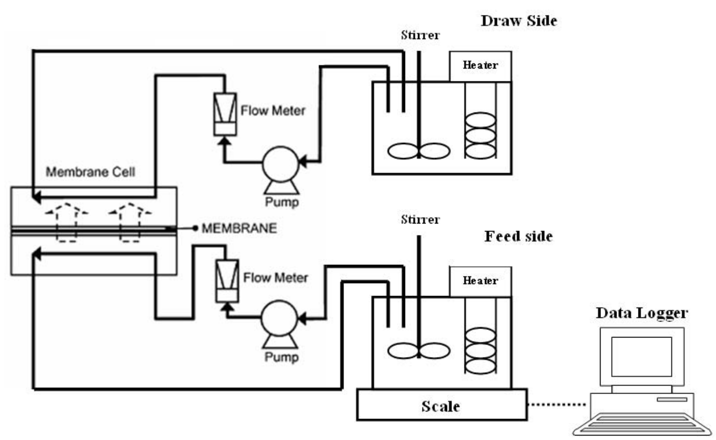


*Figure 2: Schematic diagram of the experimental Set-up (software: Microsoft Word 2003)*

The schematic diagram of the experimental set-up as shown in Figure 2 above depicts the main apparatuses used in this study. The heater is used to maintain a constant temperature of the solutions throughout the experiment. The stirrer ensures that the solutions are homogenous and the pump keeps a constant cross flow rate across the membrane. The scale which is connected to the data logger is used to measure the change in mass of the feed solution to calculate the water flux, which is given in cubic metre per square metre of membrane per second (m/s) or gallons per square feet per day (GFD).

The feed solution that is used is either deionized water or 0.5M NaCl, which simulates seawater. The concentration of the draw solutions used, namely glucose, fructose, magnesium sulfate, magnesium chloride, calcium chloride and potassium chloride ranges from 3.0 to 4.0 M. The properties of the solutions, such as the osmotic pressure are calculated using the software, OLI StreamAnalyzer 2.0. The FO membrane (Hydration Technologies Inc., Albany, OR) used is made from cellulose acetate and is highly hydrophilic. It consists of a woven support mesh embedded within the membrane.

The FO membrane is tested either in the normal mode (i.e. the dense selective layer of the membrane faces the draw solution while the porous layer faces the feed solution) or in the reverse mode (i.e. the dense selective layer facing the feed solution while the porous layer faces the draw solution). The effect of membrane orientation on transport phenomenon of the FO process is shown in Figure. 3. This figure has been included here to illustrate the development of the concentration polarization effects.

For the FO process, the normal mode is expected to have a higher water flux since the impact of internal concentration polarization (ICP) on the feed solution is smaller than that on the draw solution. Hence the FO process should be ideally conducted in the normal mode, which is also the mode adopted by commercially available FO membrane for FO process (i.e. Hydration Technologies Inc., Albany, OR).

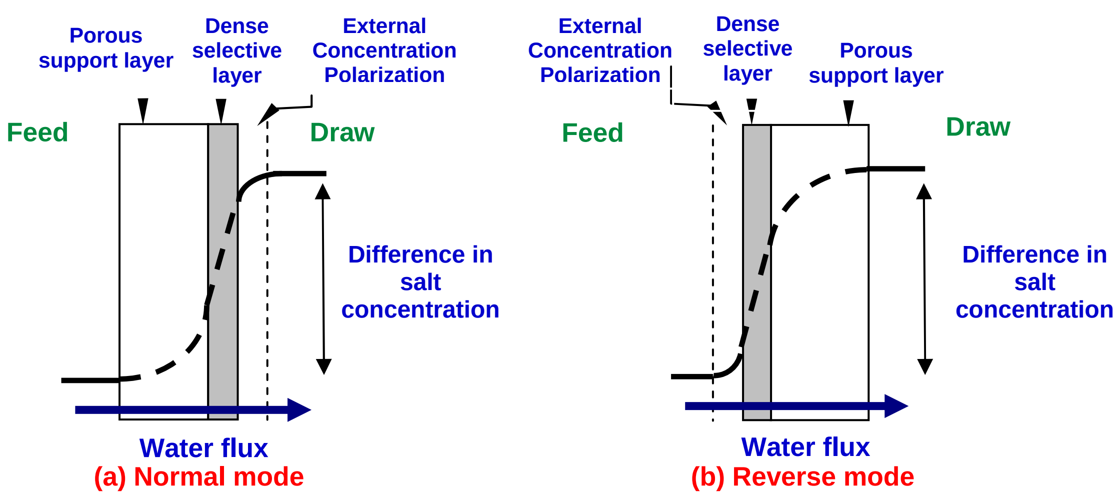


*Figure 3: Schematic diagram of the effect of membrane orientation on FO transport phenomenon (software: Microsoft PowerPoint 2003)*

The experiments are conducted using a specially designed cross-flow membrane cell which has a symmetric channel on each side of the membrane. The draw and feed solutions flow on the permeate side and co-currently on the feed side, respectively, both of which are controlled independently by a centrifugal pump and the flow-rates are measured with a flow-meter. The volumetric flow-rates for the experiments varies from

2.0 to 4.0 L/min. Both the feed and draw solutions are maintained at 25°C by using heaters with temperature controllers and are kept homogenous by two independent mechanical stirrers. A weighing scale connected to a computer with a data logging software is used to monitor the weight changes of the draw solution due to the water flux across the membrane, from which the water flux was calculated.

The water flux is calculated from the weight changes of the draw solution using the equation as shown below.

$$\textit{Water flux} = \frac{\Delta \textit{Weight}}{\textit{Time interval x Density x Area}}$$

## RESULTS AND DISCUSSION

### 3.1 Comparison of draw solutes

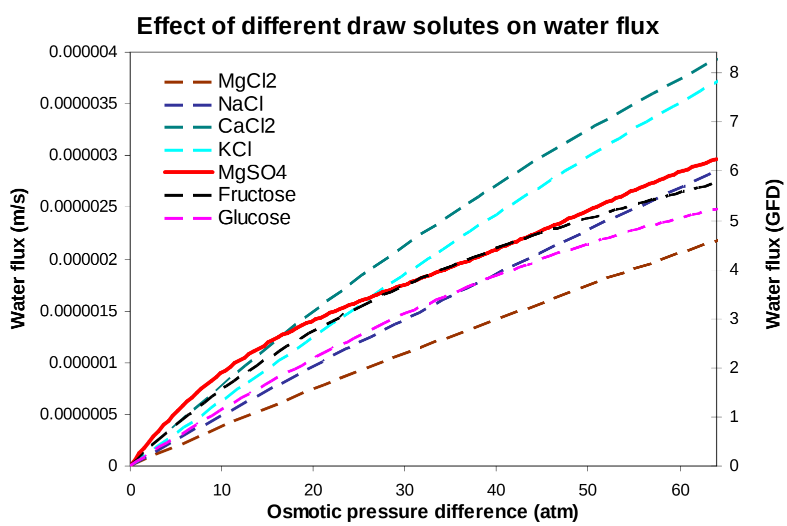


*Figure 4: Graph of effect of different draw solutes on the water flux (m/s) (software: Microsoft Excel 2003)*

Figure 4 shows the plots of experiment results of water flux against osmotic pressure difference for different draw solutions. $CaCl_2$ and KCl produced the highest water flux among all the draw solutes as they are highly soluble in water and can potentially achieve a much larger osmotic pressure. The water flux obtained by these two solutes was approximately 33.3% more than that of $MgSO_4$, making the FO process more efficient. However, $Cl^-$ anions are relatively small and cannot be effectively removed via NF process. In fact, the rejection of $Cl^-$ anions via NF was only about 60% which is incapable of producing clean product water. It must be noted that other technologies, such as RO, can be chosen for the removal of $Cl^-$ anions. However, the cost required will be much higher as compared to the use of NF, hence; NaCl and KCl are not suitable as draw solutes.

$MgCl_2$ and NaCl produced a slightly lower water flux than $MgSO_4$. Besides, $Cl^-$ anions cannot be effectively removed via NF process. $Cl^-$ anions can only be effectively removed via RO which requires a high amount of energy. Therefore, $MgCl_2$ and NaCl are inferior to $MgSO_4$ and should not be chosen as the best draw solute.

Glucose and fructose are relatively bigger molecules as compared to the other salts tested, thus they are easily removed via NF process. However, they produced a lower water flux than $MgSO_4$. Since $MgSO_4$, glucose and fructose are all easily removed via NF; $MgSO_4$ is a more suitable draw solute due to its higher flux.

Although the production of water flux by $MgSO_4$ draw solution was not the highest, the molecular size is relatively bigger than the other solutes which can produce a higher water flux. Hence, $MgSO_4$ molecules can be easily removed via NF process. Therefore, due to the efficient removal and relatively high water flux, it can be concluded that $MgSO_4$ is the most appropriate draw solute for effective FO process.

## ***3.2 Orientation of the FO membrane***

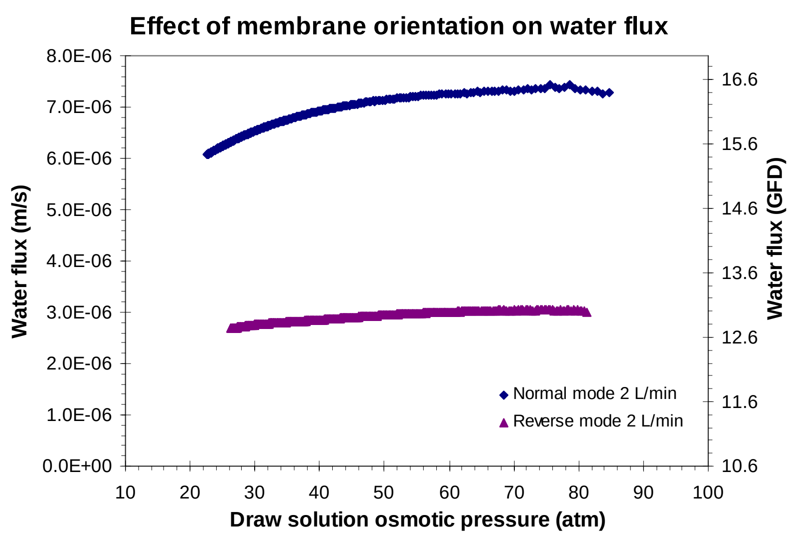


*Figure 5: Graph of effect of membrane orientation on the water flux (software: Microsoft Excel 2003)*

The FO membrane consists of two layers, namely the porous and the non-porous layer. In order to determine if the reverse or normal mode is a better choice, deionized water was used as the feed solution in the experiment to find out the maximum water flux which can be obtained. Figure 5 shows the effect the membrane orientation has on the water flux (m/s). It can be observed that when the membrane was tested in normal mode, the water flux obtained was about twice that of the water flux obtained when the membrane was tested in reverse mode. This is because the impact of the ICP experienced in the normal mode is smaller as compared to the reverse mode. Hence, the normal mode would be preferred for FO operations to obtain a relatively higher water flux.

***3.3 Comparison of FO process flow rate***

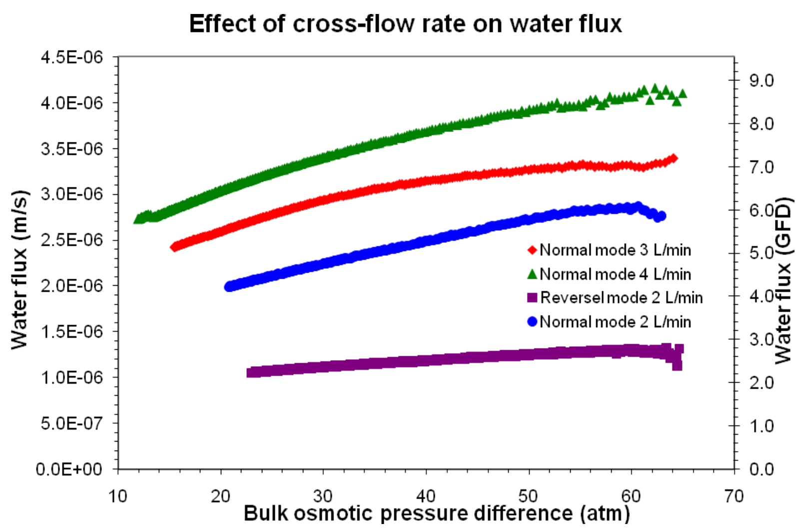


*Figure 6: Graph of effect of flow rate on the water flux (software: Microsoft Excel 2003)*

It is theorized that the cross-flow rates of the FO experiments can affect the water flux. Figure 6 shows the effect of the cross-flow rates on water flux. It can be observed from Figure 6 that as the cross-flow rate was increased from 2.0 to 4.0 L/min, the water flux was also increased. Therefore, it can be concluded that higher cross-flow rate would result in a higher water flux. This is because when the cross-flow rate is increased, higher turbulence in the flow channel will decrease the impact of ECP. In addition, a comparison with the experiment carried out in reverse mode shows that the water flux in normal mode was remarkably larger than the water flux in reverse mode.

In order to be comparable to RO, the water flux achieved should be at least 10.0 GFD, however, when the flow rate was 4.0 L/min, the maximum water flux achieved was approximately 9.0 GFD. Although the water flux obtained from the FO process may not be able to match up to that of the water flux obtained from the RO process, the energy required in the FO process is significantly lesser. As this is an emerging new technology, the FO process can be improved further. One aspect of improvement to increase the water flux is to reduce the ICP experienced in the FO process, thus the FO membrane should be as thin as possible. In order to achieve this, the porous layer of the FO membrane should be thinner but at the same time, able to provide sufficient support for the entire FO membrane. Alternatively, we can replace $MgSO_4$ with a draw solute that is able to achieve a higher osmotic pressure as well as to be removed with a more energy efficient technology. One example can be the use of magnetic nano-particles as the draw solute for the FO process that is currently being developed in NUS.

## CONCLUSION

The FO process can be an alternative membrane technology for water reclamation due to its low energy requirement, high water recovery and high solute rejection. The main objective for this project is to investigate the feasibility of using $MgSO_4$ as the solute for the draw solution in the FO process. $MgSO_4$ was compared with other draw solutes and observed to be the most suitable draw solute with a relatively high osmotic pressure and water flux. It is also discovered that FO membrane in the normal mode could produce a high water flux than the reverse mode. Finally, $MgSO_4$ could be easily removed via NF. In conclusion, the FO process is comparable to the RO process in terms of water flux and it utilizes significantly lower amount of energy. Additional improvements can be made to the FO membrane structure to further increase the water flux.

## POSSIBLE FUTURE RESEARCH

Additional improvements can be made to the FO membrane structure to further increase the water flux. Firstly, we can reduce the impact of ICP experienced by making the porous layer as thin as possible but at the same time ensuring that it will provide enough support for the entire membrane. Secondly, a new draw solute can be developed that can achieve higher osmotic pressure than $MgSO_4$ and can be removed with a more energy efficient technology. Currently, NUS is experimenting on a magnetic nano-particle draw solute.

## ACKNOWLEDGEMENTS

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