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JUDUL : SIMULATION ON THE EFFECT OF TEMPERATURE ON FORWARD OSMOSIS PROCESS ACROSS MEMBRANE

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SIMULATION ON THE EFFECT OF TEMPERATURE ON FORWARD OSMOSIS PROCESS ACROSS MEMBRANE

by

NURULHIDAYAH BINTI ROSLI

Thesis submitted in fulfillment of the requirements for the degree of
Bachelor of Chemical Engineering

January 2013

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion this thesis has fulfilled the qualities and requirement for award of Degree of Bachelor of Chemical Engineering (Chemical).

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STUDENT'S DECLARATION

I declare that this thesis entitled "Simulation on the effect of temperature on forward osmosis process across membrane" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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This thesis is dedicated to my lovely parent;

Mr. Rosli bin Ngarpani & Mdm. Maimon binti Nemat

Beloved Siblings;

Nurul Asyikin & Nurul Ain Suraya

and

Supportive lecturers and true friends

For their endless love, support and encouragement.

I will never forget any of you..

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ABSTRACT

Forward Osmosis (FO) is one of the technologies that show a great performance in energy production and water supply. Forward osmosis is more preferred in both productions especially water supply because the purity of the water produce by forward osmosis technology is higher than other technology only by using low temperature, low pressure and low energy in the operation and also has low operating cost. The purposes of this research are to develop a process model program on forward osmosis process across the membrane and to use the develop model in order to investigate how the difference of temperature and concentration of draw solutions affects the forward osmosis process. The scopes of this research are more focus on the temperature where the range is from 20°C to 40°C, concentration of draw solution which is sodium chloride (NaCl) is from 1.0M to 2.5M and the type of membrane used is cellulose triacetate membrane (CTA). Besides, the simulation program is built based on the formulas adopted from a number of journals which are related to this research by using MATLAB software. By using the developed process model, the water purity produce was higher as the temperature and draw solution concentration increase. The results shown by the simulation are the same with the experiment result from other researcher. It shows both temperature and concentration has an important impact to water flux in forward osmosis process. Besides, this forward osmosis process model can be used as a foundation of the future research.

ABSTRAK

Forward Osmosis merupakan salah satu teknologi yang menunjukkan prestasi besar di dalam penghasilan tenaga dan bekalan air. Forward osmosis lebih banyak digunakan di dalam kedua industry terutama bekalan air kerana ketulenan air yang dihasilkan melalui proses forward osmosis adalah tinggi berbanding teknologi lain dengan hanya menggunakan suhu yang rendah, tekanan yang rendah, serta tenaga dan kos yang digunakan di dalam operasi ini juga sangat rendah. Tujuan penyelidikan ini dilakukan adalah untuk membina model simulasi terhadap process forward osmosis merentasi membran dan menggunakan model tersebut untuk mengkaji bagamaina perubahan suhu dan kepekatan cecair draw mempengaruhi proses forward osmosis. Penyelidikan ini lebih fokus kepada suhu di mana jurangnya adalah dari 20°C sehingga 40°C, kepekatan cecair draw iaitu natrium klorida (NaCl) adalah dari 1.0M sehingga 2.5M dan jenis membrane yang digunakan ialah membrane cellulose triacetate. Disamping itu, program simulasi ini dibina berdasarkan formula-formula yang diperolehi dari beberapa buah jurnal yang berkaitan dengan kajian ini dengan menggunakan perisian MATLAB. Dengan menggunakan model yang telah dibangunkan, ketulenan air yang dihasilkan akan meningkat sepertimana meningkatnya suhu dan kepekatan cecair draw. Hasil simulasi yang diperolehi adalah sama dengan hasil eksperiment yang diperolehi oleh penyelidik lain. Ini menunjukan bahawa kedua-dua suhu dan kepekatan memberi kesan penting di dalam proses forward osmosis. Selain itu, model proses forward osmosis in boleh digunakan sebagai asas kepada kajian akan datang.

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LIST OF EQUATIONS

General equation for water flux in the absence of polarization:

$$J_w = A\,(\pi_{D,b} - \pi_{F,b}) \qquad (1)$$

Van’t Hoff Law :

$$\pi_{F,m} = \beta_{F,s}\, C_{F,m} R T_{F,m} \qquad (2)$$

$$\pi_{D,m} = \beta_{D,s}\, C_{D,m} R T_{D,m} \qquad (3)$$

$$\pi_i = \beta_{F,s}\, C_i R T_i \qquad (4)$$

Modified water flux formula :

i) Active layer – Draw solution mode (AL-DS)

$$J_w = A\left(\pi_{D,m} - \pi_i\right) = A\beta R\,\left(C_{D,m} T_{D,m} - C_i T_i\right) \qquad (5)$$

ii) Active Layer – Feed solution mode (AL-FS)

$$J_w = A\left(\pi_i - \pi_{F,m}\right) = A\beta R\,\left(C_i T_i - C_{F,m} T_{F,m}\right) \qquad (6)$$

Concentration and dilution polarization :

$$\frac{C_m}{C_b} = \exp\left(-\frac{J_w}{k}\right) \qquad (7)$$

i) Active layer – Draw solution mode (AL-DS)

$$\frac{C_i}{C_{F,m}} = \exp\ (K_m J_w) \tag{8}$$

ii) Active layer – Draw solution mode (AL-DS)

$$\frac{C_i}{C_{D,b}} = \exp\ (-K_m J_w) \tag{9}$$

Water permeability coefficient:

$$A = \frac{D_{eff}\, C_w V_w}{\delta_m R T_i} \tag{10}$$

$$D_{eff} = D\left[1 - \frac{d_s}{d_p}\right]^4 \tag{11}$$

$$D = \frac{9.4x10^{-15} T_i}{\mu_w M_w^{1/3}} \tag{12}$$

$$\mu_w = \rho_w \upsilon_w \tag{13}$$

Mass transfer coefficient :

$$k = \frac{Sh\ .D_s}{d_h} \tag{14}$$

Sherwood number :

1. Laminar flow : $Sh = 1.85\left(R_e Sc \frac{d_h}{L}\right)^{1/3}$ (15)
2. Turbulent flow : $Sh = 0.04\, R_e{}^{3/4} Sc^{1/3}$ (16)

Solute diffusivity:

$$D_s = 8.931x10^{-10}\left[\frac{n^+ + n^-}{n^+ n^-}\right]\left[\frac{\gamma^+\gamma^-}{\gamma^+ + \gamma^-}\right]T \quad (17)$$

Reynolds number :

$$R_e = \frac{uL}{v} \quad (18)$$

Schmidt number :

$$Sc = \frac{v}{D_s} \quad (19)$$

Kinematic viscosity of NaCl solution:

$$\frac{v}{v_w} = 1 + eC_s \exp\left[\frac{C_s{}^f}{gT_R + i}\right] \quad (20)$$

$$v_w = 9.607x10^{-8} \exp\left[\frac{2.9}{T_R{}^3}\right] \quad (21)$$

$$T_R = \frac{T}{273.15} \quad (22)$$

Equivalent conductivity of the ions:

$$\gamma^{\pm} = \gamma_{298.15}^{\pm,0} + \ell_1^{\pm}(T - 298.15) + \ell_2^{\pm}(T - 298.15)^2 + \ell_3^{\pm}(T - 298.15)^3 \quad (23)$$

Solute resistivity :

$$\mathrm{K_m} = \frac{\tau\delta_m}{\varepsilon D_s} \quad (24)$$

Heat flux:

$$Q = h_{FS}(T_{F,b} - T_{F,m})$$

$$= C_p J_w \rho_w (T_{F,b} - T_{D,b}) - h_m (T_{D,m} - T_{F,m})$$

$$= h_{DS}\ (T_{D,m} - T_{D,b}) \qquad (25)$$

Temperature near membrane surface:

$$T_{F,m} = \frac{h_m\left[T_{D,b} + \frac{h_{FS}}{h_{DS}} T_{F,b}\right] + h_{FS} T_{F,b} - C_p J_W \rho_W (T_{F,b} - T_{D,b})}{h_m + h_{FS}\left[1 + \frac{h_m}{h_{DS}}\right]} \qquad (26)$$

$$T_{D,m} = \frac{h_m\left[T_{F,b} + \frac{h_{DS}}{h_{FS}} T_{D,b}\right] + h_{DS} T_{D,b} + C_p J_W \rho_W (T_{F,b} - T_{D,b})}{h_m + h_{DS}\left[1 + \frac{h_m}{h_{FS}}\right]} \qquad (27)$$

Temperature at interface at support and active layer:

$$T_i = \frac{T_{F,m} + T_{D,m}}{2} \qquad (28)$$

Overall heat transfer coefficient of FO membrane:

$$h_m = \frac{\varepsilon \lambda_w + (1-\varepsilon)\lambda_m}{\delta_m} \qquad (29)$$

Modified solute diffusivity equation:

$$D_s = 8.931x10^{-10}\left[\frac{n^+ + n^-}{n^+ n^-}\right]\left[\frac{\gamma^+ \gamma^-}{\gamma^+ + \gamma^-}\right] T \qquad (30)$$

NOMENCLATURE

A	water permeability coefficient (m/sPa)
C	solute molar concentration (mol/L)
C_i	solute molar concentration at interface of SL and AL (mol/L)
C_p	Specific heat (J/kgK)
Ds	diffusion coefficient (m^2/s)
dp	diameter of membrane pore (m)
d_h	hydraulic diameter of the channel (m)
h	heat transfer coeeficient (W/m^2K
J_w	water flux (L/m^2h)
k	mass transfer coefficient (m/s)
K_m	solute resistivity (s/m)
L	characteristic length of the channel (m)
M_w	water molecular weight (g/mol)
n^+	valent of cations (dimensionless)
n^-	valent of anions (dimensionless)
Q	heat flux (W/m^2)
R	universal gas constant (J/molK)
Re	Reynolds number (dimensionless)
Sc	Schmidt number (dimensionless)

Sh	Sherwood number (dimensionless)
T	absolute temperature (K)
T_i	absolute temperature at interface SL and AL (K)
u	solution flow velocity (m/s)
V_w	water molar volume (m^3)

Greek letters

β	van't Hoff coefficient (dimensionless)
γ^+	equivalent conductivity of cations (cm^2/Ω)
γ-	equivalent conductivity of anions (cm^2/Ω)
δ_m	overall thickness of membrane (m)
ε	porosity of porous support layer (dimensionless)
μ	dynamic viscosity (kg/ms)
v	kinematic viscosity (m^2/s)
π	osmotic pressure (Pa)
ρ	solution density (kg/m^3)
τ	tortuosity of porous support layer

Subscript

D, b	bulk draw solution
D, m	membrane surface draw solution
DS	draw solution
F, b	bulk feed solution

F, m	membrane surface feed solution
FS	feed solution
m	membrane
W	water

CHAPTER ONE

INTRODUCTION

1.1 Background of Proposed Study

Forward osmosis (FO) is an osmotic pressure which separates water from dissolved solutes from low to high osmotic pressure region through a semi-permeable membrane (Zhao & Zou, 2011). Forward osmosis is said to be an emerging technology that shows a great performance in water supply and energy production and it is mostly preferred in desalination, wastewater treatment, food and pharmaceutical processing fields (Zhao et al., 2012). Unlike the former method, forward osmosis has potential in achieving high water flux besides it only use low energy which leads to low operating cost and also operates in low temperature and pressure (Cath et al., 2006; Zhao & Zou, 2011).

1.2 Problem Statement

Forward osmosis is a remarkable new technology that turns muddy, contaminated water or seawater into new clean water that can be drink. There are many factors that affecting the rate of forward osmosis in order to obtain a high water flux. Some of the factors are temperature and concentration of draw solution. As forward osmosis is a new technology, there is no simulation programme been developed (Choi et al., 2011) however, only a few modelling programme for forward osmosis process across the membrane had been developed. Thus, this study intends to know the effect of temperature and concentration of draw solution on forward osmosis process across the membrane through a simulation programme.

1.3 Research Objectives

This study is guided by the following research objectives:

1.3.1 To build a simulation programme of the forward osmosis process.

1.3.2 To investigate the effect of temperature on forward osmosis process across the membrane.

1.3.3 To investigate the effect of draw solution concentration on forward osmosis process across the membrane.

1.4 Scope of Study

This research is focus on the effect of temperature and concentration of draw solution on forward osmosis across the membrane by using MATLAB programme in order to develop the simulation process. Besides that, the type of membrane used in this forward osmosis process is cellulose triacetate (CTA) membrane.

1.5 Expected Outcomes

From this research, it is expected that the results from the simulation process model will be the same as the results obtained from experiments from other researchers. The purity of the water will be higher as temperature and draw solution concentration increase. This is due to several factors where the higher the temperature and concentration, it will cause the decreased of fluid viscosity and concentration polarization while at the same time the water permeability and mass transfer coefficient will increased. Thus, a higher water flux is obtained (Zhao & Zou, 2011). The model is essentially a set of different equations that describes the changes taking place across the cellulose triacetate (CTA) membrane.

1.6 Significance of Proposal Study

The developed simulation model can be used as foundation of the future research in forward osmosis since it will allow the user to study and understand the relationships between the elements of the system without having to manipulate the actual system. This will certainly give many advantages to the users to investigate the process or system rather than using the real process in term of money and time.

1.7 Conclusion

This report is divided into five chapters which are introduction, literature review, mathematical model of forward osmosis, results and discussion and conclusion and recommendation. Chapter one is divided into seven sub topics which are background of proposed study, problem statement, research objective, scope of proposed study, expected outcome, significance of proposed study and conclusion of the chapter. The second chapter consists of introduction of the chapter, the synthesis of all related articles and summary of the chapter. In chapter three, it includes the chapter introduction, the research methodology and summary. Chapter four consists of introduction, the result obtained from the research and the discussion made on the result. For chapter five, it will consist of conclusion and recommendation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The review of literature of this research study consists of six sections. Section 2.1 is the review on forward osmosis background and section 2.2 is the parameters of the forward osmosis. Review on the forward osmosis application and membrane will be on section 2.3 and 2.4. The forward osmosis previous study is review in section 2.5 and 2.6 will be the conclusion.

2.2 Forward Osmosis Background

Forward osmosis is one of the new technologies used in the water treatment especially seawater and brackish water desalination and for the purification of the contaminated water sources (McGinnis, 2005). Generally, this technologies is highly used in industrial field because of its capability to remove difficult solutes in a waste streams. Forward osmosis is referred as a process that involves osmotic membrane where it diffuses polluted water spontaneously through a semi-permeable membrane from a low osmotic region (feed solution) to high osmotic region (draw solution) in order to produce hygienic water which can be drink safely (Cath et al., 2006; Gruber et al., 2011; Jung et al., 2011; Liu et al., 2009; Xu et al., 2010; Zhao & Zou, 2011).

Figure 2.1 show the process of forward osmosis. In forward osmosis, the membrane is located in between of feed solution and draw solution (permeate). During the process, the contaminated water will directly separate from the feed solution. The feed solution is used by the draw solution to force the water to pass through the semi-permeable membrane and as a result, the draw solution will be diluted while the feed solution will be more concentrated. Due to this reason, the initial concentrations of both feed and draw solution will not be equal. The semi-permeable membrane will acts as an obstacle to block all the larger molecules from passing through the membrane and only allows the small molecules such as water to pass through it.

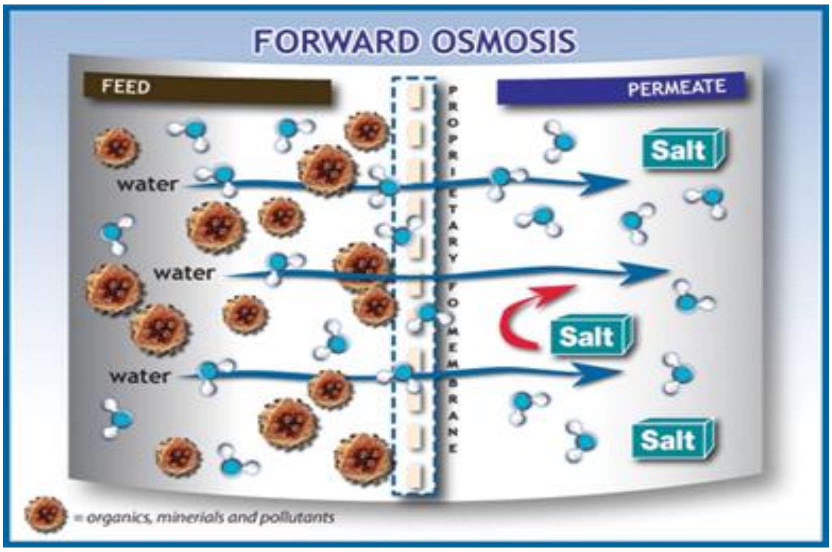


Figure 2.1 Forward Osmosis Process (*Source : HTI Water Technology)*

Forward osmosis is said as an emerging technology due to its potential to reduce the shortage of water and energy (Cath et al., 2006; Chung et al., 2012). Before forward osmosis, there are many other ways that have been used throughout the years to treat the water and one of the methods is by osmosis. Along with the technology development, the usage of the osmosis method is extended from water treatment to power generation. This is because water obtained from this method is more pure and the process is much easier. In past few years, the latest technology which is forward osmosis is introduced to the industries. Due to the potential shown by forward osmosis in water supply and power generation, forward osmosis is mostly preferred in wastewater treatment, desalination, power generation and food processing fields (Zhao et al., 2012). Differ with reverse osmosis, forward osmosis is more preferred because it can be conducted in low hydraulic pressure, has low membrane fouling and requires less energy which leads to lower cost (Cath et al., 2006; Zhao et al., 2012). Besides the water treatment and power generation, forward osmosis also have been used for others applications.

2.3 Applications of Forward Osmosis

Recently, this forward osmosis technology is applied to a range of industries. This technology is separated into three fields which are life science, water and energy (Zhao et al., 2012). In the life science fields, forward osmosis are extensively used in food and pharmaceutical processing (Cath et al., 2006; Zhao et al., 2012). In food processing, forward osmosis is usually used to concentrate beverages and liquid foods. Since the forward osmosis process can be operated at low temperature and pressure, it helps to maintain the food quality and nutritional value such as flavour, aroma, colour and vitamins (Cath et al., 2006). For pharmaceutical industry, forward osmosis helps in controlling the drugs release (Cath et al., 2006).

As for water and energy, it is applied in wastewater treatment (Cath et al., 2006; Qin et al., 2009), landfills leachate (Cath et al., 2006), seawater desalination (Kessler & Moody, 1976; McCutcheon et al., 2005; Zhao et al., 2012) and power generation (Yip et al., 2010). Landfill leachate contains many types of pollutants such as organic and inorganic compounds, dissolved heavy metals and total dissolved solids (TDS). Normally, landfill leachate is treated by using the wastewater treatment facility. However, among all of the compounds contains in the landfill leachate, the TDS is not only untreated but on the other hand enlarged the concentration of the TDS (York et al., 1999). Thus, in order to treat the TDS, forward osmosis has been used and it is proved that forward osmosis is very efficient in treating landfill leachate (York et al., 1999). Before forward osmosis is introduced, desalination and water treatment was treated by using the former membrane technologies such as reverse osmosis. However, energy issue had been arise when the former technologies was used (Fane, 2011).

Forward osmosis also has been used for osmotic bioreactor membrane and direst fertigation which is for the fertilizers. For all of this applications, forward osmosis is preferred due to several benefits where it can operates in low hydraulic pressure (Cath et al., 2006; Gruber et al., 2011) and higher osmotic pressure (Zhao et al., 2011). Low hydraulic pressure leads to lower tendency of the membrane to foul (Gruber et al., 2011) where lower membrane fouling caused the water product to be increased and longer the membrane life (Zhao et al., 2012). Besides, forward osmosis only requires low energy consumption for water transport (Chung et al., 2012; Zhao et al., 2012). As a consequences from the lower energy needed, it can reduce the process costs and increase the water flux produce by forward osmosis (Zhao et al., 2012). In order to obtain pure water with a higher water flux in the water treatment, there are many parameters involved which can affect the rate of forward osmosis.

2.4 Parameters in Forward Osmosis

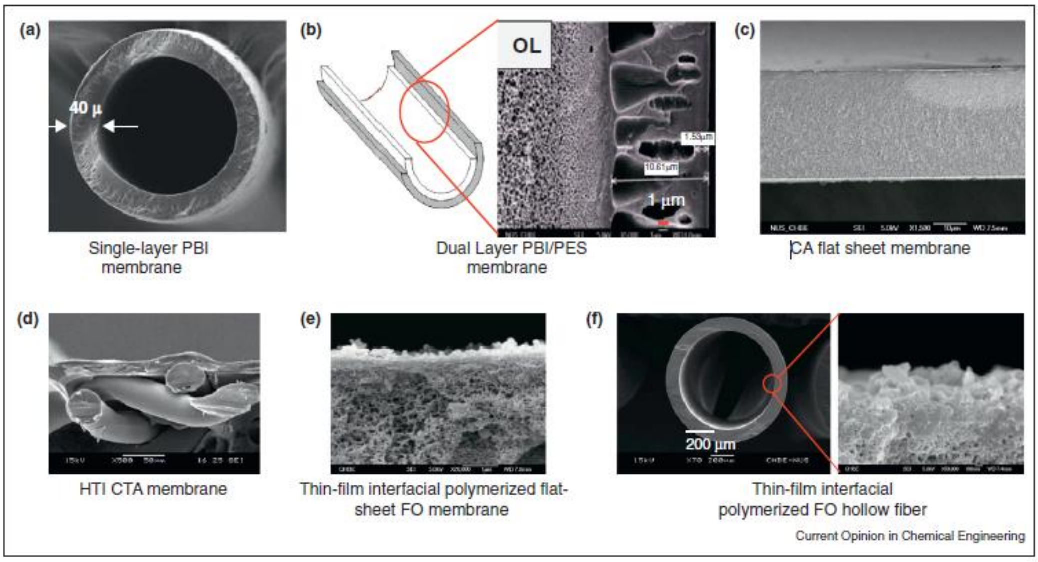
In forward osmosis, there are several factors that influenced the rate of osmosis such as temperature (Choi et al., 2011; Zhao & Zou, 2011), surface area (Wang et al., 2009) , concentration (Nayak & Rastogi, 2010) , membrane orientation (Gruber et al., 2011; Zhao et al., 2011) and pressure (Choi et al., 2011). Each of this factor have their own role in the osmosis process in order to produce pure and clean water that can be securely drink by human. For the surface area, the molecules can move across the membrane easily when the surface area is larger while the movement of the molecules will be slower and restricted when the surface area is smaller. The concentration gradient will also affect the rate of the osmosis where when the concentration of the solute is lower within the solvent, the rate of osmosis occur will be faster in that solvent.

As for the pressure, when a high pressure is applied, the molecules will move faster as they are being pushed by the pressure to the low concentration region. Among all these factors, this study is more focus on the effect of temperature and the concentration of the draw solution where the water flux produce will be depends on both parameters. The movement of the water molecules across the semi-permeable membrane will be faster as the temperature is higher. Besides, Zhao and Zou (2011) had stated that the water flux will be higher as the temperature increase. This is due to several factors that are closely related to the temperature or known as temperature

– dependent. The factors are the fluid viscosity, concentration polarization, permeability of water and the mass transfer coefficient.

2.5 Forward Osmosis Membrane

Membrane is a crucial element in forward osmosis. This is because membrane acts as a filter where it is located between the feed and draw solution. It needs to filter the feed solution such as seawater and isolates the solutes or salts from the seawater when the seawater pass through the membrane from feed solution to draw solution. There are many types of membranes that can be used in the osmosis process such as single-layer polybenzimidaofe (PBI), Dual layer PBI/ polyesthersulfone (PES), cellulose acetate (CA) flat sheet membrane, cellulose ester (CE) membrane, cellulose triacetate (CTA) membrane, thin-film interfacial polymerized flat-sheet FO membrane and thin-film interfacial polymerized FO hollow fiber. Figure 2.2 shows some of the types of membranes used in forward osmosis process for water reuse and desalination. Each of the membrane used has different characteristics and has affected the results.



Some of typical FO membranes for water reuse and desalination. **(a)** Single-layer polybenzimidazole (PBI) membrane[1]; **(b)** Dual Layer PBI/polyethersulfone (PES) membrane[2]; **(c)** CA flat sheet membrane[3]; **(d)** Hydration Technology Innovations (HTI) CTA membrane; **(e)** Thin-film interfacial polymerized flat-sheet FO membrane[4]; and **(f)** Thin-film interfacial polymerized FO hollow fiber[5].
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Figure 2.2 Types of typical FO membrane used *(Source: Chung et al. (2012a))*

For the forward osmosis membrane, it is desired to have several characteristics in order to obtain clean water. The membrane must have high salt retention and water flux. In addition, the membrane must also have a low concentration polarization, resistance to chlorine and wide pH range as well as separation stability performance and mechanical strength for long-term (Chung et al., 2012). According to Cath et al. (2006), the characteristics of the forward osmosis membranes are high density upon the active layer for the rejection of the high solute. Besides, the membrane need to be thin and has the support layer need to has a minimum porosity in order to ontain a higher water flux. This is because when the membrane is thick, it will lead to concentration polarization and the water flux and driving force produce is decreased (McCutcheon et al., 2005).

The latest commercialize forward osmosis membrane that has been used nowadays is the cellulose triacetate (CTA) membrane which is provided by Hydration Technologies Innovation (HTI, Albany, Oregon). Based on figure 2.3, it shows that the overall thickness of the CTA membrane is approximately 50µm which is very thin. Thus, this membrane is suitable to be used for the forward osmosis process since it is very thin and has lower porosity and can be able to reduce the concentration polarization (Cath et al., 2006). The characteristic of the active layer and the support layer of the CTA membrane is denser and fibrous compared to other types of membrane (Low, 2009). As a result, the water flux generate is higher and the water can be drink safely. Generally, it can be said that any membrane which is denser, permeable and non-porous can be used in forward osmosis process.

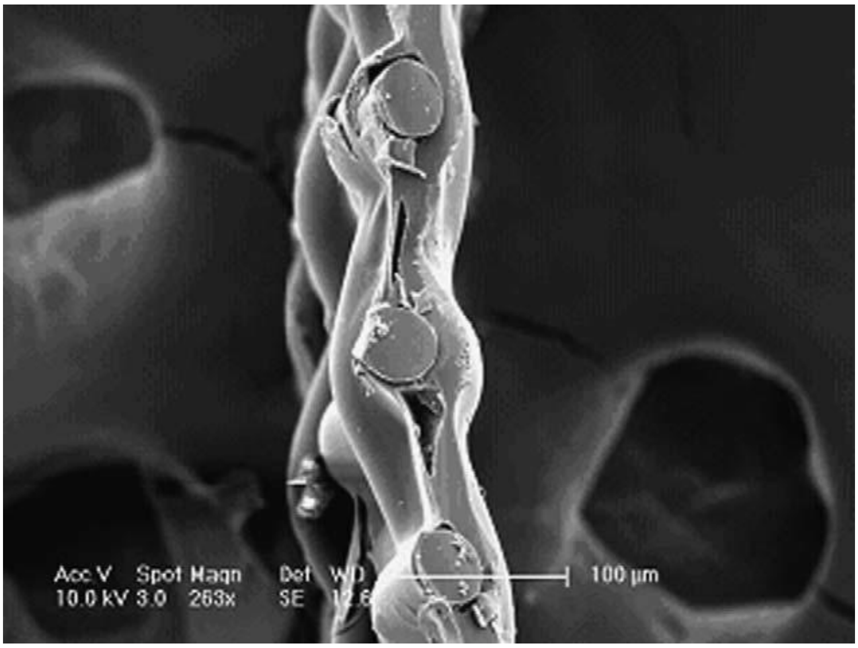

Figure 2.3 A cross-sectional image of CTA membrane. The thickness of membrane is less than 50µm. *(Source: McCutcheon et al. (2005))*

2.6 Comparison between Reverse Osmosis and Forward Osmosis

Before forward osmosis been introduced, the technology used to purify and treat the contaminated water is the reverse osmosis (RO) method. Reverse osmosis is also a membrane process where the hydraulic pressure is controlling the process (Choi et al., 2009). Besides that, there are many problems rises when the reverse osmosis method is used in water treatment. Using this methods higher energy is required (McCutcheon et al., 2005; Zhao & Zou, 2011) and cause higher membrane fouling (Zhao & Zou, 2011). Due to this problems, the water flux produce is lower and the process costs is higher (Zhao & Zou, 2011). In reverse osmosis, the membrane used is very thin which is less than 1μm and has thicker porous layer (Cath et al., 2006). This membrane cause a higher concentration polarization because of the porosity of the support layer. Thus, forward osmosis is introduced in order to overcome the limitation of the reverse osmosis technology. The different between forward osmosis and reverse osmosis is shown in Figure 2.4.

From the figure, it shows that the pressure required for forward osmosis is much lower than reverse osmosis where the pressure range is only 25 PSI while reverse osmosis is in between 400 to 1100 PSI. When the pressure used for the process in lower, the tendency of the membrane fouling occures will be lower. The tendency for the membrane to foul is said to be lower because the solution which contains contaminants will pass through the membrane naturally without being force by the pressure. By this way, all the contaminants will be left out and only small particles such as water can pass through the membrane. Besides the pressure, it also shows that the type of the membrane used for both process is different where the membrane used for forward osmosis is more permeated than for reverse osmosis.

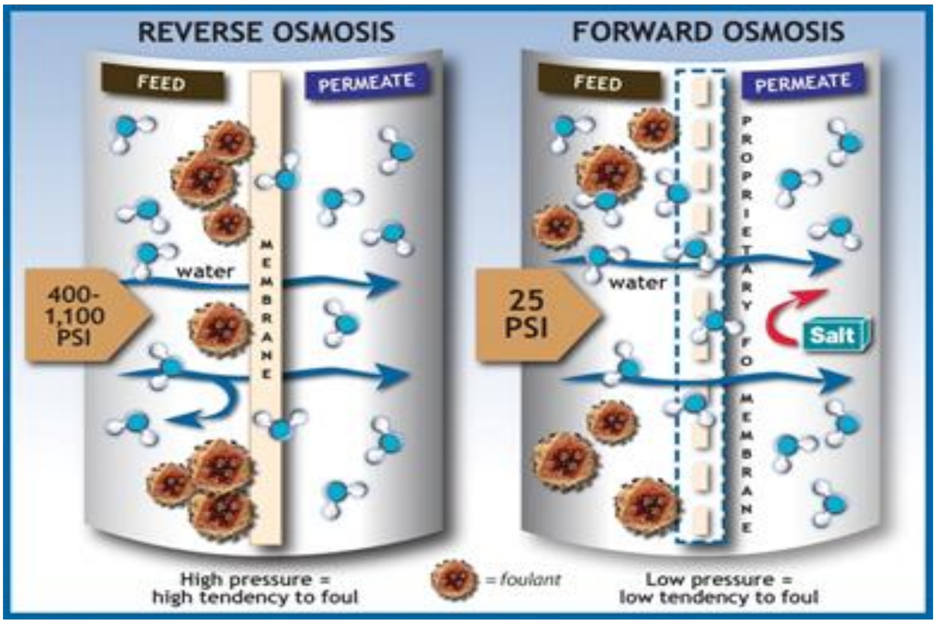

Figure 2.4 Difference between forward osmosis and reverse osmosis *(Source : HTI Water Technology)*

In addition, Liu et al. (2009) has stated that reverse osmosis process is more preferred for a normal separation system while forward osmosis is for the sensitive system such as temperature-sensitive system, pressure-senstive system and drug release controlled. The water recovery from both processes are different where for reverse osmosis it is between thirty to fifty percent differ from forward osmosis which is seventy five percent. Between reverse osmosis and forward osmosis, forward osmosis process is more environmental friendly rather than reverse osmosis and has a low investment for the equipment of the process. Table 2.1 shows the summary of the comparison between forward osmosis and reverse osmosis.

Table 2.1 Summary of the comparison between forward osmosis and reverse osmosis *(Source: Liu, et al., (2009))*

Sort	Reverse Osmosis	Forward Osmosis
Driven Pressure	High hydraulic pressure	Osmosis pressure difference
Water Recovery	30%～50%	At least 75%
Environment Effect	Harmfully	Friendly
Membrane Fouling	Seriously	Hardly
Modules	Compression resistance	Without particular desire
Application	Normal separation system	Temperature-sensitive system; Pressure-sensitive system; Renew energy; Controlled Release of drug
Energy Consumption	High energy expenditure	Low energy demand
Equipments	High-pressure pumps; Energy recovery unit; Resistant high-pressure pipelines; High investment in equipments	Low investment in equipment

2.7 Previous Study on Forward Osmosis

Throughout the years, there are many research on forward osmosis technology has been done. Based on the previous study, the most important elements in producing high water flux are the type of the membrane used and usage of the draw solution (Cath et al., 2006). In forward osmosis, draw solution is used to generate a driving force in order to persuade the flow of the water to pass through the membrane (Pearce, n.d). According to McCutcheon et al. (2005), many methods in improving the forward osmosis technology has been done by researches where different types of membrane and draw solution was used. However, the results is not very satisfied.

One of the method is by using cellulose acetate membrane and glucose solute dissolved in seawater as draw solution. As a result, the salts is not well rejected by the cellulose acetate membrane (Kravath & Davis, 1975). Another method is by McGinnis (2002) where the draw solution is combined with several membranes in a two stages forward osmosis. The author used a saturated potassium nitrate solution as draw solution. The potassium nitrate enter the second forward osmosis unit where the draw solution is the dissolved sulfur dioxide. Due to the lower osmotic pressure of potassium nitrate, it is rejected when both of the solution pass through the membrane. As a result, the sulfur dioxide solution did not have enough osmotic pressure thus it is not considered using it as a draw solution.

In former method, most of the researched done was using reverse osmosis membrane where the result gained was not satisfied since the membrane is thicker than the forward osmosis membrane. Besides that, the types of the membrane module also affected the production rate of the water flux. Membrane have two possible types which can be apply to forward osmosis process which are flat sheet membrane and tubular membrane. However, between this two membrane, the researched done are normally focused on flat sheet membrane for both lab-scale and large-scale applications (Gu et al., 2011). Flat sheet membrane consists of two module which are plate-and-frame module and spiral-wound module. Plate-and-frame module consists of flat sheet membrane and spacers where both are staked into the metal frame such as illustrate in figure 2.5. The flow direction of the draw solution to pass through the membrane are changed according to the flow orientation either co-current flow, counter-current flow or cross-current flow.

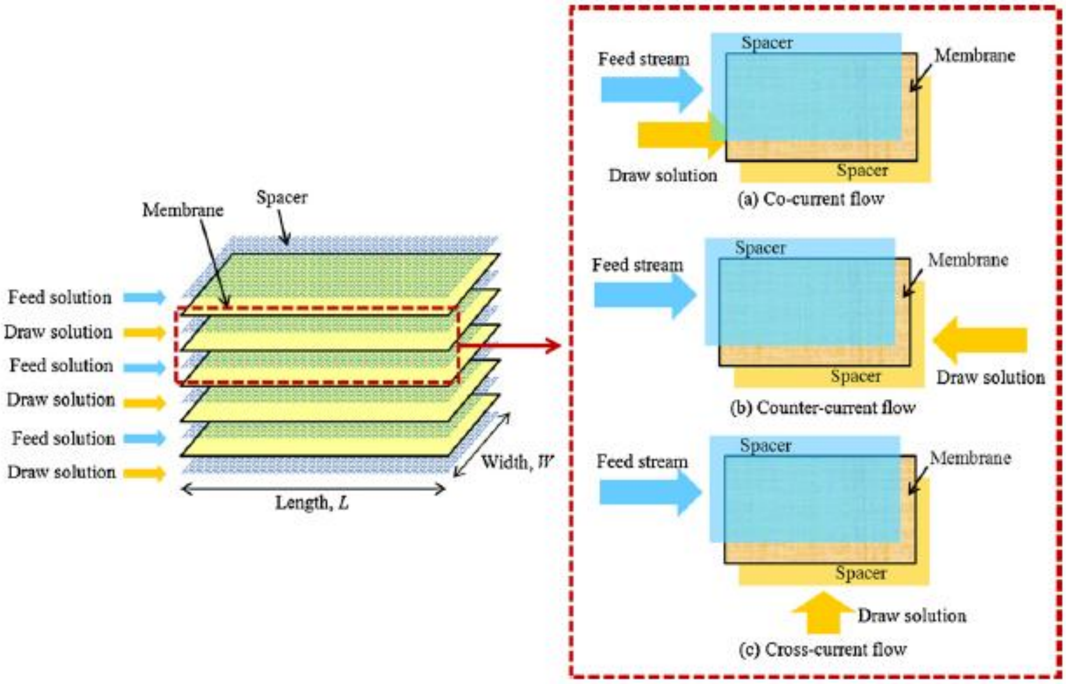

Figure 2.5 Plate-and-frame module schematic diagramand possible flow directions of two solutions *(Source : Gu et al., 2011)*

As for the spiral-wound module, the flat sheet membrane is winding around a central pipe. This module allow two inlet streams which can be pass through the module where one stream flows outside the enveloped in length direction while another one stream flows inside the envelope as shown in figure 2.6. Typically, the spiral-wound module is used for the reverse osmosis process. The performance for both modules was study under similar parameters and the membrane geometry (Gu et al., 2011). As a result, the water flux produced from each module was higher as the flow rate and the draw solution concentration higher. The rate of the water flux depends on the geometry and orientation of the membrane as well as the solution locations.

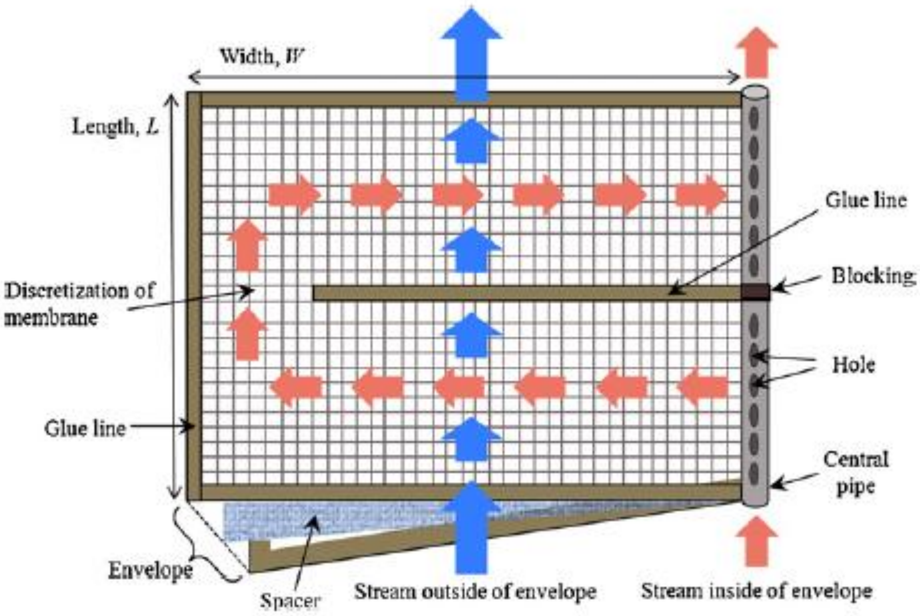

Figure 2.6 Modified spiral-wound schematic diagram *(Source : Gu et al., 2011)*

From the study above, it shows that the selection of the membrane and draw solution is important in forward osmosis and it must be appropriate. The draw solution must have higher osmotic pressure in order to obtain higher water flux and water recovery (McCutcheon et al., 2005). To gain higher osmotic pressure, the draw solution must be highly water soluble along with low molecular weight. It also must be non-toxic, can be separate easily and economically (McCutcheon et al., 2005;

Wang et al., 2012). From this reviews it shows that all the researchs on forward osmosis that had been done in previous study mostly focus on the experimental work and there is no research on simulation for overall forward osmosis process is made. Thus, this research study is proposed.

2.8 Conclusion

Based on the journals and articles, there are some research that had been done on this study before. This forward osmosis technology is better than other membrane process such as reverse osmosis because it only need a small energy and can operates under low temperature and pressure and the process costs is cheaper than reverse osmosis. In order to achieve a high water flux, the draw solution and the type of membrane choose must be appropriate.

CHAPTER THREE

MATHEMATICAL MODEL OF FORWARD OSMOSIS

3.1 Introduction

This chapter will explain more details on the mathematical model of forward osmosis of this research study. This chapter consists of four sections where section 3.1 will be the introduction and 3.2 is MATLAB software. Section 3.3 is the equation used and the conclusion of the chapter will be on section 3.4.

3.2 MATLAB Software

The programme used in this study to develop the simulation of the forward osmosis is matrix laboratory or commonly known as MATLAB. This software is widely used in academic and research institution and also industries. MATLAB is a programming environment for numerical computation, data analysis and visualization and also for the development of algorithm. The technical computing problem can be faster and easily solve by using this software rather than the older programming software. In this study, MATLAB version 7.10 or R2010a is used to develop the simulation. This version is used because it has better tools installed rather than the older versions. Thus, it can help in developing the simulation of the forward osmosis to be faster and easier without having many problems.

3.3 Equations in Forward Osmosis

There are several equations that will be used in developing the simulation programme on the effect of temperature of forward osmosis. All of the equations are used in order to obtain the higher water flux by using different temperatures. The mathematical model for forward osmosis across CTA membrane in this work adopted from S. You et al., (2012).

In general, the equation for water flux, J_w in the absence of polarization is expressed as:

$$J_w = A\,(\pi_{D,b} - \pi_{F,b}) \tag{1}$$

where A is the pure water permeability coefficient, $\pi_{D,b}$ and $\pi_{F,b}$ is the osmotic pressure of bulk draw solution (DS) and feed solution (FS). The osmotic pressure is related to the concentration and temperature and it is calculated by using the Van't Hoff modified equation (Phuntsho, et al., 2012):

$$\pi_{F,m} = \beta_{F,s}\, C_{F,m} R T_{F,m} \tag{2}$$

$$\pi_{D,m} = \beta_{D,s}\, C_{D,m} R T_{D,m} \tag{3}$$

$$\pi_i = \beta_{F,s}\, C_i R T_i \tag{4}$$

where *C* and *T* is the concentration and temperature while the subscripts F,m, D,m and i are the FS and DS at membrane surface and at the interface of the membrane. R is the gas constant (8.314J/mol.K) and β is the van't Hoff coefficient where the value for sodium chloride (NaCl) is equal which is $\beta=\beta_{DS}=\beta_{FS}=2.0$. When Eqs. (1),(2),(3) and (4) are combined, the water flux is written in the modified form:

$$J_w = A(\pi_{D,m} - \pi_i) = A\beta R\,(C_{D,m}T_{D,m} - C_iT_i) \qquad (5)$$

or

$$J_w = A(\pi_i - \pi_{F,m}) = A\beta R\,(C_iT_i - C_{F,m}T_{F,m}) \qquad (6)$$

For the modified form, there are two types of equations where Eqs. (5) is used to determine the water flux at the active layer – draw solution (AL – DS) mode while Eqs. (6) is used to determine the water flux at the active layer – feed solution (AL – FS) mode.

During the forward osmosis process, phenomena called concentration polarization (CP) will occur where the solute concentration near the membrane and in the bulk were linked together and calculated by using equation below.

$$\frac{C_m}{C_b} = \exp\left(-\frac{J_w}{k}\right) \qquad (7)$$

where k is the mass transfer coefficient which are related to Sherwood number, Sh. However, since there are two modes, AL-DS and AL-FS, different equation was used to calculate the concentration in each mode. For AL-DS mode,

$$\frac{C_i}{C_{F,m}} = \exp\,(K_mJ_w) \qquad (8)$$

and for AL-FS mode,

$$\frac{C_i}{C_{D,b}} = \exp\ (-K_m J_w) \tag{9}$$

K_m is the solute resistivity C_i, $C_{F,m}$ and $C_{D,b}$ is the concentration at interface of the membrane at support layer (SL) and active layer (AL), membrane feed solution and bulk draw solution.

The water permeability coefficient was predicted by using equation

$$A = \frac{D_{eff}\, C_w V_w}{\delta_m\, RT_i} \tag{10}$$

The value of A is approximately 2.0×10^{-12} m/sPa, D_{eff} is effective water molecule diffusivity within AL membrane pores, C_w is water molar concentration (0.18 g/cm^3), V_w is molar volume of water (18cm^3/mol) and δ_m is the membrane thickness.

$$D_{eff}\ = D\left[1 - \frac{d_s}{d_p}\right]^4 \tag{11}$$

The value of D_{eff} was calculated by using Eqs. (11) where D is the apparent diffusivity, while d_s (4.0Å) and d_p (7.2Å) is the diameter of the water molecule and the water pore.

$$D = \frac{9.4x10^{-15} T_i}{\mu_w M_w^{1/3}} \tag{12}$$

$$\mu_w = \rho_w \upsilon_w \tag{13}$$

where M_w is the molar mass of water while μ_w is the dynamic viscosity of water. To calculate the mass transfer coefficient, k the Sherwood number, Sh, solute diffusivity, Ds and hydraulic channel diameter, d_h was needed. In this research the size of the channel used is 7.8cm x 2.5cm x 0.5cm which produced an effective area of 19.5cm^2 along with the total volume of 9.75cm^3.

$$k = \frac{Sh\ .D_s}{d_h} \tag{14}$$

Sherwood number :

1. Laminar flow : $Sh = 1.85 \left(R_e Sc \frac{d_h}{L}\right)^{1/3}$ (15)
2. Turbulent flow : $Sh = 0.04\, R_e^{3/4} Sc^{1/3}$ (16)

$$D_s = 8.931x10^{-10} \left[\frac{n^+ + n^-}{n^+ n^-}\right] \left[\frac{\gamma^+ \gamma^-}{\gamma^+ + \gamma^-}\right] T \tag{17}$$

where Eqs.(15) is used for laminar flow while Eqs.(16) is used for turbulent flow. *Re* is Reynolds number, Sc is Schmidt number. n^+ and n^- is the valent of cations and anion (n =1) while γ^{+} is the equivalent conductivity of the ions. The equation for Reynolds and Schmidt number is written as:

$$R_e = \frac{uL}{v} \tag{18}$$

$$Sc = \frac{v}{D_s} \tag{19}$$

where u is solution flow velocity, L is characteristic length of the channel and v is viscosity of NaCl. The value of v is obtained by:

$$\frac{v}{v_w} = 1 + eC_s \exp\left[\frac{C_s f}{gT_R + i}\right] \tag{20}$$

$$v_w = 9.607x10^{-8} \exp\left[\frac{2.9}{{T_R}^3}\right] \tag{21}$$

$$T_R = \frac{T}{273.15} \tag{22}$$

which v_w is water viscosity, e = 0.12, f = -0.44, g = -3.713, i = 2.792, C_s is NaCl molar concentration and T_R is the normalized temperature. The equation for the equivalent conductivity is:

$$\gamma^{\pm} = \gamma_{298.15}^{\pm,0} + \ell_1^{\pm}(T - 298.15) + \ell_2^{\pm}(T - 298.15)^2 + \ell_3^{\pm}(T - 298.15)^3 \tag{23}$$

where $\gamma_{298.15}^{\pm,0}$ ($5.1 \times 10^{-3} m^2/\Omega$ for sodium ion; $7.64 \times 10^{-3} m^2/\Omega$ for chloride ion) at 298.15K; temperature coefficient $\ell_1^+ = 1.092$, $\ell_2^+ = 4.72 \times 10^{-3}$, $\ell_3^+ = -1.15 \times 10^{-5}$ for Na^+ and $\ell_1^- = 1.540$, $\ell_2^- = 4.65 \times 10^{-3}$, $\ell_3^- = -1.28 \times 10^{-5}$ for Cl^-.

The solute resistivity, K_m is calculated from the equation below:

$$K_m = \frac{\tau \delta_m}{\varepsilon D_s} \tag{24}$$

where τ is the tortuosity and ε is the porosity of the membrane.

In the presence of temperature different, heat transfer will take place across the membrane. However, according to the heat transfer principle, the heat flux, Q will remain unchanged. Thus,

$$\begin{aligned} Q &= h_{FS}\left(T_{F,b} - T_{F,m}\right) \\ &= C_p J_w \rho_w \left(T_{F,b} - T_{D,b}\right) - h_m\left(T_{D,m} - T_{F,m}\right) \\ &= h_{DS}\,(T_{D,m} - T_{D,b}) \end{aligned} \tag{25}$$

where h is the individual heat transfer coefficient, Cp is the specific heat of water, ρ_w is the water density.

The temperature at membrane feed solution and draw solution is calculated by using:

$$T_{F,m} = \frac{h_m \left[T_{D,b} + \frac{h_{FS}}{h_{DS}} T_{F,b}\right] + h_{FS} T_{F,b} - C_p J_W \rho_W (T_{F,b} - T_{D,b})}{h_m + h_{FS}\left[1 + \frac{h_m}{h_{DS}}\right]} \quad (26)$$

$$T_{D,m} = \frac{h_m \left[T_{F,b} + \frac{h_{DS}}{h_{FS}} T_{D,b}\right] + h_{DS} T_{D,b} + C_p J_W \rho_W (T_{F,b} - T_{D,b})}{h_m + h_{DS}\left[1 + \frac{h_m}{h_{FS}}\right]} \quad (27)$$

$$T_i = \frac{T_{F,m} + T_{D,m}}{2} \quad (28)$$

h_m is the overall heat transfer coefficient, Ti is the temperature at the interface of the membrane SL and AL.

$$h_m = \frac{\varepsilon \lambda_W + (1-\varepsilon)\lambda_m}{\delta_m} \quad (29)$$

$\boldsymbol{\lambda_w}$ = 0.02 W/mK from previoius study.

3.4 Conclusion

This chapter had discussed on the mathematical model of forward osmosis. By using the MATLAB software and equations above, the simulation on the effect of temperature of forward osmosis can be develop.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

The main purposes of this research is to build a simulation programme on forward osmosis across the membrane process and to use the develop model to investigate the effect of temperature and concentration of draw solution on forward osmosis process across the membrane. In order to achieve the objectives, the simulation was built by using MATLAB software. As a result, the parameters effects were observed and the water flux, J_w was obtained.

In this study, several of the constants used were changed. The constants changed were the pure water permeability, A, and the solute diffusion coefficient, Ds. Based on the researched paper referred, the original value for pure water permeability, A is 2.0 x 10^{-12} m/sPa. However, for this study the value used is $2x10^{-10}m/sPa$. For solute diffusion coefficient, Ds the original equation is as stated in Eqs. (17) is changed to:

$$Ds = 8.931x10^{-7}\left(\frac{n^{+}+n^{-}}{n^{+}n^{-}}\right)\left(\frac{\gamma^{+}\gamma^{-}}{\gamma^{+}+\gamma^{-}}\right)T \qquad (30)$$

The values of the constants were changed in order to obtain the similar water flux pattern from the reference used. These changes need to be done because of some of the mathematical model was not used in this process model in order to reduce the complex calculation.

4.2 Effect of concentration on water flux

Figure 4.1 shows the simulation was run at different concentration of draw solution with the presence of temperature different. Four sets of draw solution concentration is used in this research which is from 1.0M to 2.5M and run for temperature 20°C, 25°C , 30°C, 35°C and 40°C. The concentration of the feed solution is fixed which is 0.1M. The graph shows that the concentration of the draw solution affects the value of the water flux with the presence of the temperature different. As the concentration increase, the value of the water flux increased. Besides, it also shows that the value of the water flux obtained in the active layer – draw solution mode is higher than the water flux obtained in active layer – feed solution. This is due to the membrane orientation itself where in this research the active layer of the membrane is facing the draw solution.

From Eqs. (1), it shows that in order to obtained the higher value of water flux, the value of the osmotic pressure need to be higher. Since the value of the osmotic pressure is depends on the concentration of the solution used, the water flux produced is affected. As in this study, the concentration of the draw solution was varies while for feed solution it is fixed to 0.1M. Thus, under this condition, when the concentration of draw solution used is higher, the water flux produced in AL-DS mode is much higher than in AL-FS mode. In addition this is also due to the presence of the concentration polarization (Zhao et al., 2012).

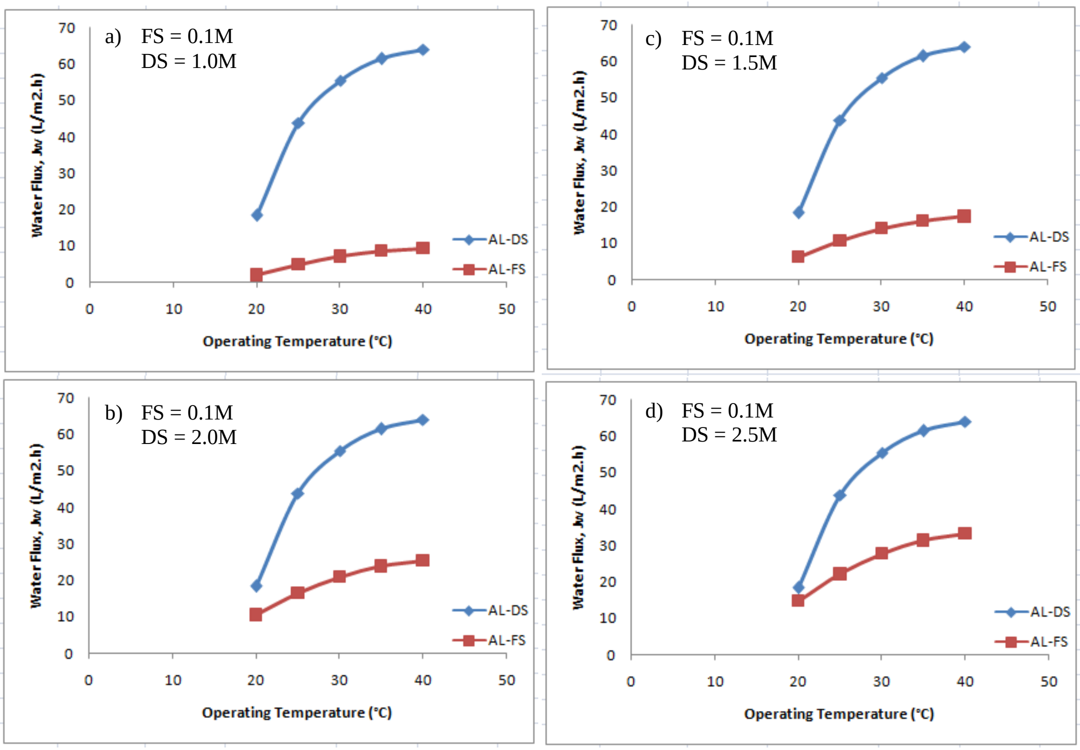

Figure 4.1 The graph of water flux vs. temperature 20°C - 40°C at different concentration of draw solution. a) water flux behaviours for draw solution, 1.0M; b) water flux behaviours for draw solution, 1.5M; c) water flux behaviours for draw solution, 2.0M; d) water flux behaviours for draw solution, 2.5M;

Concentration polarization (CP) is a transport phenomenon which occurs in the osmosis-driven membrane process. There are two types of CP which are known as external concentration polarization (ECP) and internal concentration polarization (ICP) (Cath et al., 2006). ECP normally occurred at the surface of the dense active layer of the membrane whereas the ICP occurred within the porous support layer of the membrane. However, ECP can be negligible since it only takes part in a slight role in forward osmosis process and not the main reason for the water flux effects

(Cath et al., 2006). On the other hand, ICP plays an important role in forward osmosis. Throughout the process, the internal concentration polarization (ICP) was occurred. It is said that when the concentration of the draw solution, C_{DS} is higher, the effects of the ICP will be more extreme. Since ICP occurred within the support layer of the membrane, thus varying the flow rates or turbulence will gives no effect to the process. This effect is related to the solute resistivity, Km where when the value of Km is smaller, the water flux obtained will be higher.

In addition, the ICP also caused the water flux produced for each mode was different where the flux produced in active layer – draw solution (AL – DS) mode will be higher than the active layer – feed solution (AL – FS) mode (You et al., 2012) as shown in figure 4.1. Since the water flux varies with the concentration of the draw solution, the concentration at 2.5M was chosen to plot water flux – temperature profile graph. This is because among all four sets of concentration of the draw solution used, the pattern of the water flux produced at concentration 2.5M was similar to the pattern obtained from the reference used. Thus, this is proved that the equation used in this study is applicable to be used in building the simulation program.

4.3 Effect of the temperature on the water flux

Figure 4.2 shows the value of the water flux produced in the process increased as the temperature increased from 20°C to 40°C. This is due to the adjustment of the solution thermodynamic properties such as osmotic pressure, viscosity and solute diffusivity (Phuntsho et al., 2012). As the value of the temperature increased, it cause the fluid viscosity in the draw solution to be reduced while the diffusion rate of the water to pass the membrane increased (Low, 2009).

From Eqs. (30) it is stated that the value of solute diffusivity is directly proportional to the temperature. Thus the value of solute diffusivity is increased as the temperature increased because at higher temperature it caused the pores of the membrane to expand and allows more solute to diffuse. Furthermore, the value of solute resistivity, K_m is also affected as the solute diffusivity changed. Based on Eqs. (24), the value of is inversely proportional to solute diffusivity. Thus, the value of solute diffusivity needs to be higher in order to obtain lower K_m. This is because the water flux produce will be higher only if the value of K_m is lower since the value of K_m is inversely proportional with water flux (Phuntsho et al., 2012; You et al., 2012). In addition, as the temperature increased, the permeability of water was also increased due to the increasing of the solution diffusion rate across the membrane.

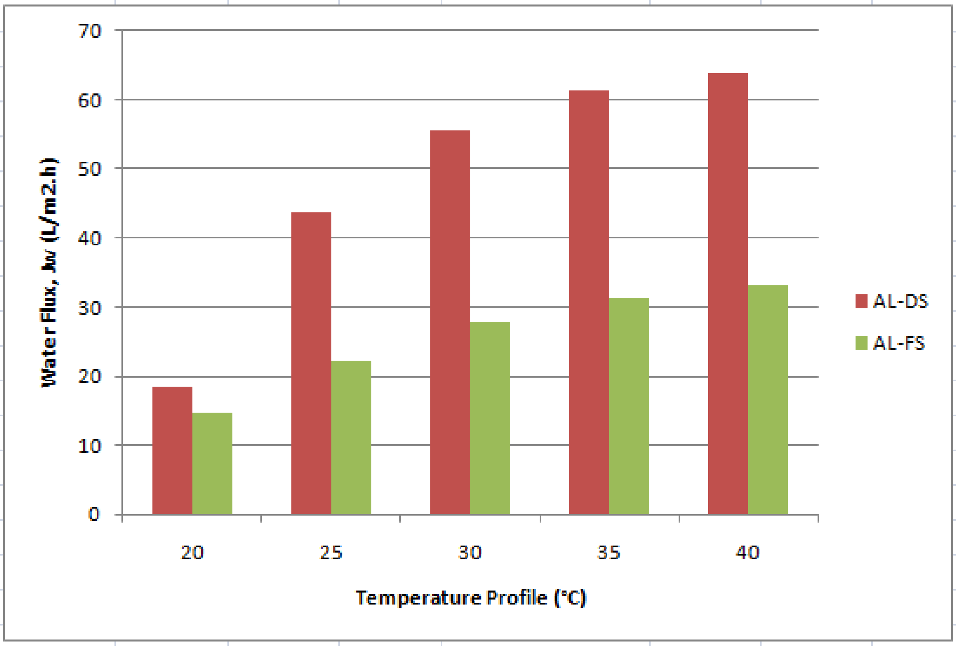

Figure 4.2 The graph of temperature profile vs. water flux

4.4 Conclusion

Temperature and draw solution concentration are the parameters that related to each other in order to obtain a higher water flux. When both temperature and draw solution concentration are varied the water flux will be affected. Based on the result obtain from the simulation programme developed, the water flux increased as the value of temperature and concentration increased. This is due to the internal concentration polarization, diffusivity, solute resistivity and viscosity of the solution. All of these factors are related with each other and are temperature – dependent. Thus, as the temperature increased, these parameters will be varied which will lead to the increased of the water flux and vice versa.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this research a simulation programme is built in order to investigate the effect of temperature and concentration of draw solution on forward osmosis process across the cellulose triacetate membrane by using MATLAB software. The temperature used for the simulation is from 20°C to 40°C while for the concentration of the draw solution used which is NaCl is from 1.0M to 2.5M. The results show that as the temperature and the concentration of the draw solution increased, the value of the water flux produced is higher. It shows that the developed process model was successfully built within MATLAB to investigate the effect of temperature and concentration. All results were compare to previous research which show good agreement with the theory. However, both temperature and concentration used must be in lower range in order to produce purified water with high water flux because of the concentration polarization. The developed process model can be used as a basis for further research on forward osmosis across membrane using cellulose triacetate (CTA) membrane.

5.2 Recommendation

To improve the developed simulation programme of forward osmosis in this research, there are several recommendations that can be considered. The recommendations are listed as below.

1) There are many others parameters such as flowrate, membrane orientation and surface area that can effects the water flux of the forward osmosis process across the membrane. Due to this reason, further study can be made on the effect of these parameters in forward osmosis process.

2) There are several simulations programme had been developed for the forward osmosis process across the membrane. However, for the whole forward osmosis process, there has no simulation programme have been developed yet. Thus, it is suggested that a simulation programme for the full process of forward osmosis can be develop in the future.

3) The types of draw solutions and its concentration influenced the rate of water flux produced in forward osmosis process. Since cellulose triacetate membrane is the latest commercialized membrane for forward osmosis process, a study on forward osmosis process by using different types of draw solutions and concentration may be made for future research.

4) In order to achieve higher water flux in producing clean water, a combine process between forward osmosis and reverse osmosis can be made. Thus it is suggested that a research on hybrid process between forward osmosis and reverse osmosis can be made in the future.

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