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PERFORMANCE EVALUATION OF PRESSURE RETARDED OSMOSIS (PRO) PROCESS FOR POWER GENERATION

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กระบวนการออสโมซิสที่หน่วงด้วยความดันเป็นเทคโนโลยีของเยื่อเลือกผ่านสำหรับการกำเนิดกำลังทางเลือก ที่ดำเนินการบนพื้นฐานความแตกต่างของความดันออสโมติกระหว่างน้ำจืดและน้ำทะเล น้ำจืดจากแม่น้ำมีค่าความเค็มต่ำซึมผ่านเยื่อเลือกผ่านไปยังอีกฝั่งหนึ่งซึ่งมีค่าความเข้มที่สูงน้ำที่ซึมผ่านเยื่อเลือกผ่านจะถูกส่งไปยังกังหันเพื่อกำเนิดกำลัง ในปัจจุบันมีงานจำนวนน้อยที่พัฒนาแบบจำลองทางคณิตศาสตร์เพื่อทำนายฟลักซ์ของน้ำ ความหนาแน่นของกำลัง และประสิทธิภาพภายใต้สภาวะเฉพาะ จุดประสงค์ของงานนี้คือเพื่อตรวจสอบผลกระทบของตัวแปรเพื่อหาสภาวะที่ดีที่สุด เช่น อัตราการไหล ทรัพยากรทางน้ำ และเยื่อเลือกผ่าน เพื่อได้รับประสิทธิภาพสูงสุดในแง่ของความหนาแน่นของกำลัง การจำลองกระบวนการของออสโมซิสที่หน่วงด้วยความดันถูกดำเนินการโดยแอสเพนคัสตอมโมเดลเลอร์ และแอสเพนซอฟแวร์ การวิเคราะห์ทางอุณหพลศาสตร์ถูกศึกษาเพื่อประเมินประสิทธิภาพของระบบ และเพื่อเปรียบเทียบกับการกำเนิดกำลังทางทฤษฎี นอกจากนี้กระบวนการออสโมซิสที่หน่วงด้วยความดันถูกขยายขนาดขึ้นสำหรับการประยุกต์ใช้งานจริง มีการประเมินต้นทุนเพื่อหาความเป็นไปได้ในการก่อสร้างโรงไฟฟ้า ผลการจำลองแสดงค่าสูงสุดของกำลังเฉลี่ยเท่ากับ 15.99 กิโลวัตต์ ประสิทธิภาพทางอุณหพลศาสตร์ภายใต้น้ำจืด และน้ำทะเลที่ใช้เป็นสารตั้งต้น โดยเยื่อเลือกผ่านชนิด แลป ทีเอฟซี-พีอาร์โอ-1 มีค่าเท่ากับ 18.20% นอกจากนั้นการใช้เยื่อเลือกผ่าน แลป ทีเอฟซี-พีอาร์โอ-1 ให้ค่าต่ำสุดของต้นทุนต่อหน่วยประมาณ 11,500 ดอลลาร์ต่อกิโลวัตต์ ท้ายสุดนี้ทรัพยากรที่มีคุณภาพต่ำคือน้ำเสีย และน้ำกร่อย สามารถใช้เป็นประโยชน์เพื่อผลิตกำลังที่เป็นมิตรต่อสิ่งแวดล้อม

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MINTRA AUPAHAD: PERFORMANCE EVALUATION OF PRESSURE RETARDED OSMOSIS (PRO) PROCESS FOR POWER GENERATION. ADVISOR: PROF. SUTTICHAI ASSABUMRUNGRAT, Ph.D., CO-ADVISOR: LIDA SIMASATITKUL, D.Eng., 49 pp.

Pressure retarded osmosis (PRO) process is an interesting membrane technology for alternative power generation operating based on difference in osmosis pressure between river water and seawater. Water from river having a low salinity permeates through a membrane to the other side where elevated pressure seawater having higher salinity flows. The permeated water is then passed through a turbine to generate power. To date, there are a few works on development of mathematical models for predicting water flux, power density, and efficiency under specific conditions. The objective of this work is to investigate the effects of parameters to find the best operating conditions such as feed flow rate, water resources and membrane to obtain the highest performance in term of power density. The process simulation of PRO is performed by using Aspen Custom Modeler and Aspen Plus software. Thermodynamic analysis was studied for evaluation efficiency of system to compare with theoretical power generation. Moreover, the PRO process is scaled up to pilot scale for practical application. The capital cost is evaluated to find the possibility in power plant construction. The results show maximum net power of 15.99 kW and thermodynamic efficiency of 18.20% under river water as feed solution and using Lab TFC-PRO-1membrane.In addition, using Lab TFC-PRO-1 membrane reports minimum unit capital cost about \$11,500 kW^{-1}. Finally, the low quality resources that is waste water and brackish water which was used to benefit for power production by environmental friendly system.

Department: Chemical Engineering Student's Signature ....
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CHAPTER 1
INTRODUCTION

1.1 Introduction

The energy resources for human activities are supported by fossil combustion which is high emissions of greenhouse gases [1]. It is accelerating climate change and global warming. To reduce the reliance on fossil fuels, new alternative sources which are environmental friendly have to be explored and studied. Nowadays only 13 % of renewable resources which are divided to 75% of biomass and waste, 17% of hydro, 6% of solar and wind and geothermal, and 2% of wave and tidal energies are available [1]. Recently the interesting technology without emission of gas and renewable energy is salinity-gradient energy, because it is based on difference in salinity concentration between river water and seawater. As a result, it is suitably controlled conditions which can generate energy [2, 3].

Pressure retarded osmosis (PRO) process is an interesting membrane technology for osmotic power generation which is based on the difference of osmosis pressure between river water and seawater. River water which is a low salinity permeates through a membrane to a high salinity side. While Hydraulic pressure is applied in the seawater side. Water can permeate through the membrane to a turbine for power generation.

To date, there are a few works on development of mathematical models for predicting water flux, power density, and efficiency under specific conditions. The objective of this work is to investigate the effects of parameters in order to find the optimal operating conditions and to obtain the highest performance in term of power density. Furthermore, the sources of water in Thailand are limited. Fresh water at feed side should be the lowest salinity. Water resources such as brine water and seawater are compared to determine the most efficient utilization of water resources. Waste water and brackish water which are useless and adversely affect on environment. It can substitute to river water; therefore, types of resources at feed side are also compared to determine the suitable water resources. The thermodynamic analysis are used to calculate theory power density and estimate efficiency of process. Moreover, economic assessment is computed to evaluate the production cost to unit of PRO plant.

1.2 Research Objectives

To study the effect of parameters such as types of membrane, operating conditions and water resources on performance of PRO process.

1.3 Scope of work

1. The PRO process was modelled using Aspen Custom Modeler software.
2. The performance of PRO under various operating conditions such as feed flow rate, water resources, and membrane types were calculated. The optimum condition was determined to obtain the most efficient utilization of water resources.
3. The thermodynamic analysis was studied in order to compare power density between theory and simulation results, then estimate efficiency.
4. The economic of process was determined to calculate the production cost in unit of power from PRO process

1.4 Expected Outputs

The performance of PRO process is investigated to find the optimal process conditions in term of maximum power density. Waste water and brackish water can be used as raw materials for power generation.

CHAPTER 2

THEORY

2.1 Theoretical potential of osmotic pressure gradient energy

Osmotic pressure gradient energy is free energy during the mixing of waters with different salt concentrations [1]. The amount of free energy from the mixing of two solutions which can be theoretically calculated in term of Gibbs energy from basic thermodynamics. For example, the free energy from mixing of 1 m^3 of seawater and fresh water can be calculated as shown in equation 1.

$$\Delta G_{mix} = G_B - \left(G_S + G_f\right) \tag{1}$$

where ΔG_{mix} (J/mol) is the change in Gibbs energy and G_B, G_S and G_f are the Gibbs energies of the resultant brackish, the seawater, and the fresh water (J/mol), respectively.

The assumption is that the solutions are ideal and the chemical (μ_i) of component i in the solution can be shown as equation 2 [2]:

$$\mu_i = \mu_i^0 + \bar{V}_i \Delta P + RTlnx_i + \left|z_i\right| F\Delta\varphi \tag{2}$$

where μ^o is the molar free energy under standard conditions (J/mol), $\bar{V_i}$ is the the specific volume of volume of component i (m^3/mol), ΔP is the pressure change compared to the atmospheric conditions (Pa), R is the gas constant (8.31441 J/K▪mol), T is the absolute temperature (K), x_i is the molar fraction of the component of the component i, z is the valence of and ion (equiv./mol), F is the Faraday constant (96,485 C/equiv.), and $\Delta\varphi$ is the different electrical potential (V).

Since there is no pressure change and charge transport, the difference in free energy can be theoretically estimated from the change of chemical potential of the system after and before mixing as shown in equation 3 [3]:

$$-\frac{\Delta G_{mix,V_A}}{\upsilon RT} \approx \frac{c_M}{\phi} ln(\gamma_{S,M} c_M) - c_A ln(\gamma_{S,A} c_A) - c_B ln(\gamma_{S,B} c_B) \frac{(1-\phi)}{\phi} \qquad (3)$$

where c is the molar salt concentration of the aqueous solutions, ϕ is the ratio of the total moles in solution A to the total moles in the system, R is the gas constant, T is temperature and υ number of ions each electrolyte molecule dissociates into. The activity coefficient, γ_i , is incorporated to account for the behavior of non-ideal solutions, and is a function of the temperature, pressure, and solution composition.

2.2 Classification of osmotic process

Osmosis is natural phenomenon which was discovered by French Scientist in 1740. Osmosis phenomenon is the movement of water across through a semi-permeable membrane due to pressure gradient between solutions of a higher chemical potential solution and a lower chemical potential which is considered as a driving force of water transport. The characteristic of semi-permeable membrane is selective water passing through a membrane but unwanted elements are not selective [4]. Osmotic processes include forward osmosis (FO), reverse osmosis (RO), and pressure retarded osmosis (PRO) process.

2.2.1 Reverse osmosis (RO) process

Reverse osmosis (RO) process was developed in the last 40 years to produce potable water from seawater. The U.S. Geological Survey found that 96.5% of Earth's water of seawater, 1.7% of ice caps and 0.8% of fresh water so water shortages problems plagued in many cities [5]. The desalination of seawater for fresh water production from reverse osmosis process has been developed over the past decades.

The principle of reverse osmosis process is to apply a high hydraulic pressure pump higher than osmotic pressure. As a result, brine water can pass across a semi-permeable membrane for fresh water production as shown in Figure 2.1. A semi-permeable membrane for this process should be thin, non-porous, selective permeable materials which can be used as selective barriers [6]. Neither salts nor elements can permeate through the membrane [5].

Reverse osmosis (RO) is a process which is used in several industries to water consumption production from water resources such as river water, seawater, or brackish water, to clean up wastewater from industrial processes and others.

Figure 2.1 Reverse osmosis (RO) process[3].

2.2.2 Forward osmosis (FO) process

Forward osmosis is a natural process, which occurs all around us on everyday basis such as transportation of water plant from roots to their leaves. a semi-permeable membrane is used for separation of water from solution [3]. The forward osmosis (FO) process consists of feed solution and draw solution stream that is higher concentration than feed solution. The feed solution can be a dilute product streams such as waste water stream or seawater.

The diffusion of water across semi-permeable membrane from feed solution into draw solution can be presented by the second law of thermodynamic. Such systems always spontaneously evolve towards a thermodynamic equilibrium state which is the maximum entropy as shown in Figure 2.2. Difference in osmotic pressure of the ideal solution can be estimated from Morse equation as shown in equation 4.

$$\Delta\pi = iMRT \tag{4}$$

when

i is The Van't Hoff factor, which reflects the dissociation multiple of the solute species insolution.

R is the gas constant in (L▪atm▪/K▪M).

T is the temperature of the solution in Kelvin (K).

M is the molarity of the solution in Molar (M).

There are 2 steps for FO osmosis. The first step is the water permeation through the membrane to produce clean water. While the second step is to regenerate draw solution.

For the second step of FO process, the recovery of draw solution has been diluted in process. Therefore, the suitable types of draw solution should be selected otherwise energy requirement is high [6]. Figure 2.3 presents types of draw solution for FO process. The suitable draw solution such as magnesium chloride ($MgCl_2$) and calcium calcium chloride ($CaCl_2$) should provide high osmotic pressure. The applications of FO process in several industries are water reuse and desalination, food and beverage, mining, oil and gas, and the power industry.

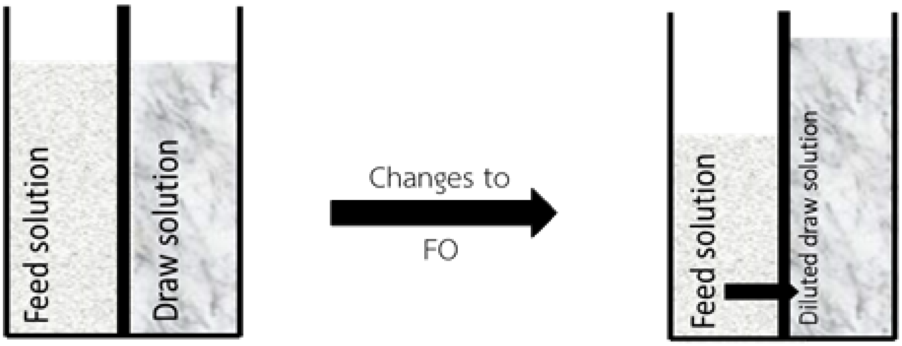

Figure 2.2 Forward osmosis (FO) process[3].

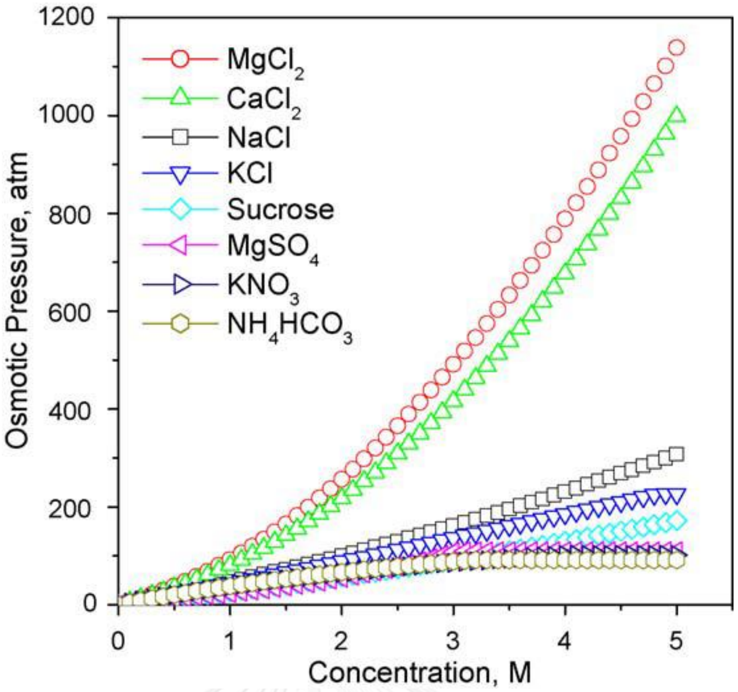

Figure 2.3 Osmotic pressure as a function of solution concentration at 25 °C for various potential draw solutions[6].

2.2.3 Pressure retarded osmosis (PRO) process

Pressure retarded osmosis (PRO) process is an interesting membrane technology for osmotic power generation which is based on difference in osmosis pressure between river water and seawater as shown in Figure 2.4.

Both feed solutions are treated prior to entering into semi-permeable membrane to remove impurities and reduce fouling effect. Then treatment salinity water is pumped to high pressure then it passes through a pressure exchanger before feeding into the semi-permeable membrane which faces the active layer of membrane. While treatment of fresh water is pumped into semi-permeable membrane by applying low pressure on the other side of membrane which faces the support layer. Fresh water passing through membrane to salty water increases volume (ΔV) of water [3]. As a result, seawater was diluted and become brackish water which is divided into two streams: the first one is to drive the turbine to produce energy and the other stream passes through pressure exchanger for energy recovery. The energy generation may not enough to required energy for treatment process. Therefore, performance of membrane should be improved by optimizating and increasing osmotic pressure. The membrane performance of PRO process is evaluated in terms of power density (W). Ideally, power density can be calculated as shown in equation 5.

$$W = \Delta P \times J_w \tag{5}$$

Where ΔP is hydraulic pressure and J_w is water flux which is calculated as shown in equation 6 when effects of concentration polarizations are neglected.

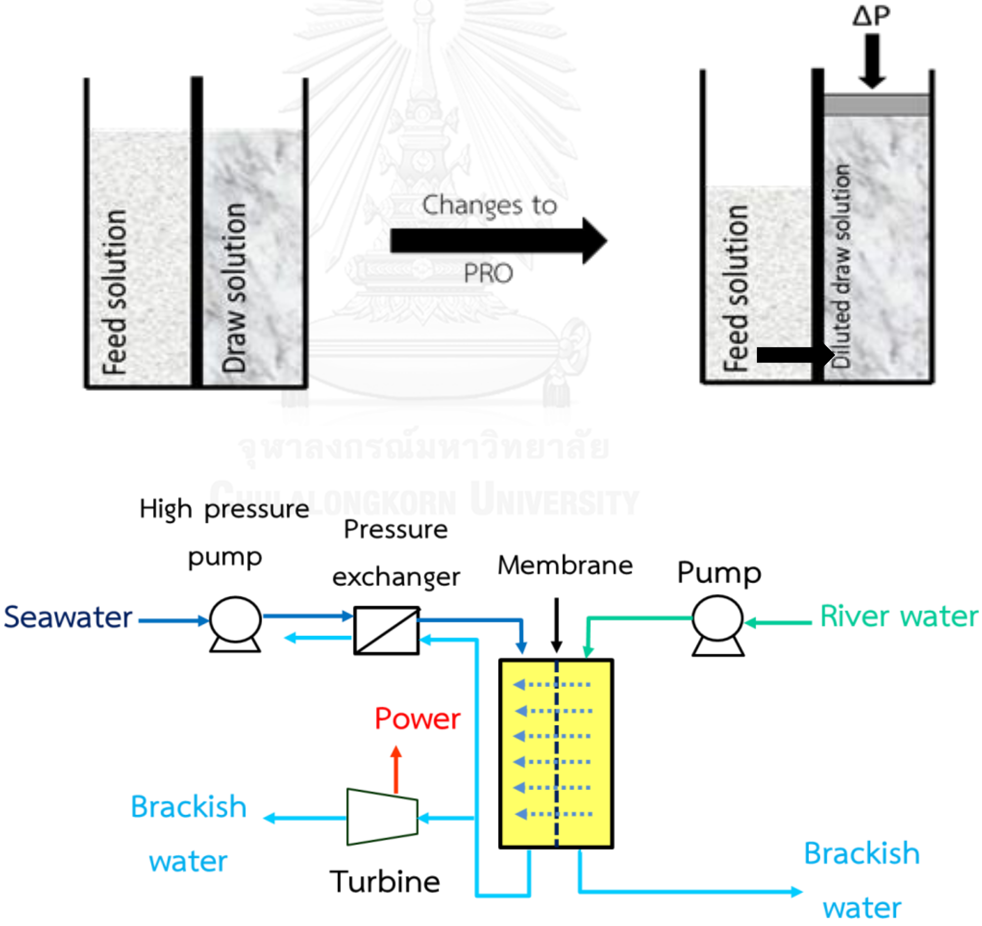

Figure 2.4 Pressure retarded osmosis (PRO) process[3].

$$J_w = A \times (\Delta\pi - \Delta P) \quad (6)$$

$$W_{max} = J_w \times \frac{\Delta\pi^2}{4} \quad (7)$$

where A is the water permeability coefficient of the membrane, $\Delta\pi$ is the different osmotic pressure between the two solutions. The theoretical maximum power density (W_{max}) occurs when ΔP equals to half of the different osmotic pressure which is shown in equation 7.

The relationship between the three phenomenon in terms of water flux and hydraulic pressures (ΔP) is presented in Figure 2.5. Applied hydraulic pressure (ΔP) of reverse osmosis (RO) process is higher than difference in osmotic pressure ($\Delta\pi$); therefore, water flux is higher than other processes. There is no water flux when hydraulic pressure (ΔP) equal to difference in osmotic pressure ($\Delta\pi$). Applied hydraulic pressure (ΔP) of pressure retarded osmosis (PRO) is lower than different osmotic pressure ($\Delta\pi$). Finally, water flowing across semi-permeable membrane by difference in osmotic pressure ($\Delta\pi$) is forward osmosis (FO) process which is natural phenomenon of two solutions due to different salt concentrations.

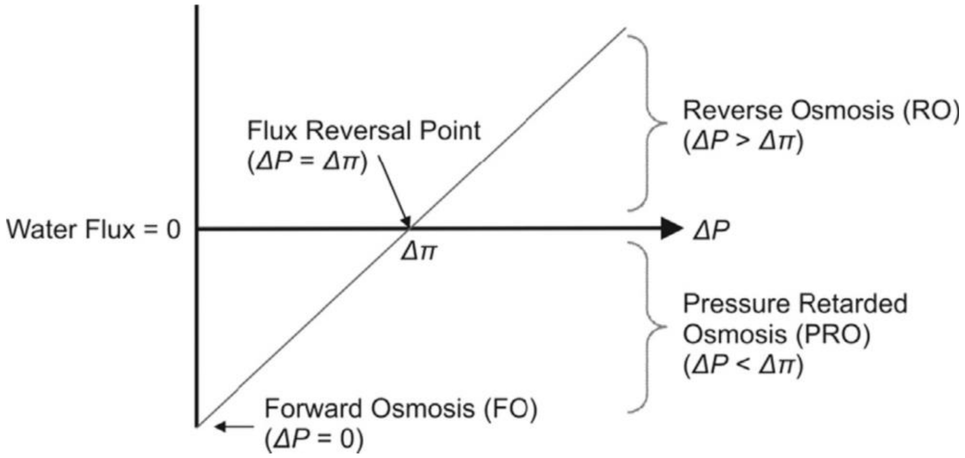

Figure 2.5 Direction of water flux as a function of hydraulic pressure (ΔP) in reverse osmosis (RO), pressure retarded osmosis (PRO) and forward osmosis (FO) process[3].

2.3 Membrane performance

Membrane performance in PRO process is usually determined in term of power density per unit area membrane [2]. The power density is important as it will directly effects on the cost of osmotic power. The capacity of the process is not only limited by the power density of membranes but availability of feed solution in the environment. Therefore, types of feed solution are significant factors operating at high efficiency. The power density of membrane may limit the activity by increasing the cost of the power production to a level that cannot make a profit. Since the late 2000s, researches of PRO process has been focusing on development of new membrane for generate power at least 5 W/m^2. The main problem of development membranes is concentration polarization which reduces water flux and power density in PRO process, as discussed in the next sections.

In previous studies, PRO process was based on RO membranes in laboratory scale. The concentration polarization was discovered that major problem is to drive water through membrane. This phenomenon was found strongly affecting to reduce water flux. The reduction of water flux decreases power density of PRO process. The concentration polarization problem was discovered by Mehta and Loeb [10, 11] and Lee et al. [12]. The concentration polarizations consist of external and internal concentration polarization.

External concentration polarization (ECP) was referred as salt concentration that occurs over time on external side of membrane (present by C_1 and C_2 in Figure 6), while internal concentration polarization (ICP) was defined as the accumulation of salt within the active layer of membrane (C_3 in Figure 2.6). It was found that salt concentration hoarding significantly decreases different osmotic pressure which drives water across membrane and power generation [6]. It means that different osmotic pressure is driven due to different C_1 and C_3 instead of different C_D and C_F.

In Figure 2.6, J is water flux of water through membrane from the dense active layer contacting with draw solution to another side of membrane. The draw solution is diluted and the concentration on interface is reduced to C_1. While the unperfected membrane enhances a counter flux of salt (J_S) from draw solution to feed solution side. During this process, the accumulation of salt at interface of membrane layer causes the reduction of the effective difference in osmotic pressure and power density. The effect of internal concentration polarization (ICP) mainly reduces power density although a small effect of difference in osmotic pressure is decreased [7]. The internal concentration polarization (ICP) is concentration polarization that results in the solute being concentrated inside the support layer. It means that ICP effect depends on properties of membrane such as porous of support layer.

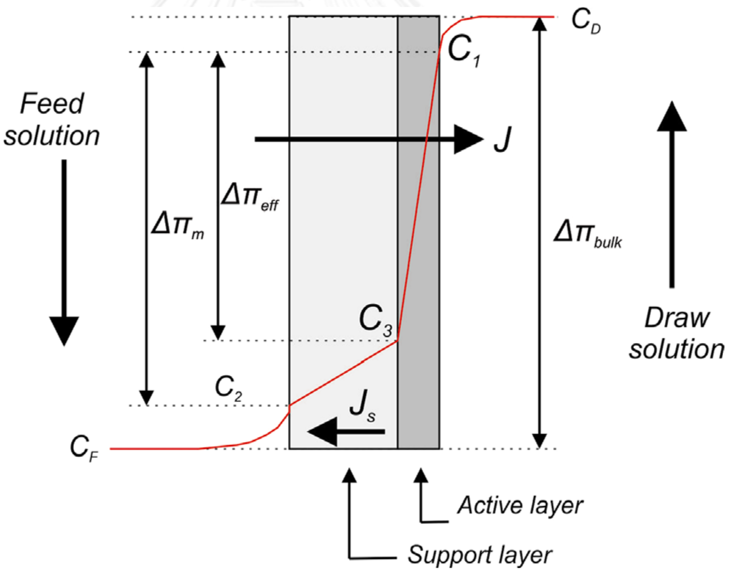

Figure 2.6 External and internal membrane concentration polarizations that occur during PRO process. C_D and C_F are the salt concentrations of the bulk feed and draw solutions, respectively. C_1 and C_2 are the salt concentrations due to external concentration polarization, and a reduced different osmotic pressure is $\Delta\pi_m$. C_3 is the salt concentration due to internal concentration polarization and an effective osmotic pressure differential is $\Delta\pi_{eff}$ [2, 6].

CHAPTER 3

LITERATURE REVIEWS

The pressure retarded osmosis (PRO) process for power generation from different osmotic pressure is an interesting issue in recent years. Despite of the advancement of PRO process, fouling effect of membrane remains a major problem in operation which may be significantly limit of performance and application of membrane. The several researches exerting studied and solved fouling problem. Xin Liu et al [13], synthesized silver nanocomposite osmotic membranes to improve water permeability and excellent anti-biofouling for use in pressure retarded osmosis (PRO) process. The results were shown that increasing of water permeability of 24.4% improved water flux from 66.9% to 88.2% and biofilms decreased fouling effect from 95.9 ± 3.2% to 69.2 ± 5.3%. , High performance thin film composite (TFC) PRO membrane was used for pressure retarded osmosis (PRO) process (Gang Han et al [14] and Ngai Yin Yip et al [15]). The TFC-PRO membrane was high water permeability (5.3 – 5.81 $Lm^{-2}h^{-1}bar^{-1}$) and also overcome the bottlenecks of low power density so TFC-PRO membrane was selected for PRO performance test. Gang Han et al [14] found that power density from pressure retarded osmosis (PRO) process was high (7 to 12 W/m^2) by using TFC-PRO membrane and can withstand a hydraulic pressure of 15 bar. When river water (10 mM of NaCl) and waste water (80mM of NaCl) were feed solutions and seawater (0.59 mM of NaCl) was considered as draw solution. This water resources can provide performance process. The highest power density of 10.0 W/m^2 when using river water as feed solution and seawater as draw solution was obtained at hydraulic pressure about 15 bar (Ngai Yin Yip et al [15]).

The performance of pressure retarded osmosis (PRO) process can be improved by optimization of operating conditions such as feed solution concentration, draw solution concentration, temperature, feed flow rate and membrane types. Thor

Thorsen and Torleif Holt [7] studied parameters such as typical commercial RO membranes (ultra low pressure type (ULP), high rejection type (HR), and cellulose acetate (CA)) that effected on power density and recovery effect. The results showed that the highest power density was 5 W/m^2 and suitable recovery was between 30 and 40 percent when using ULP membrane. The effect of membrane types which directly affected to internal concentration polarization were studied so suitable membrane should be selected (Gang Han et al [3]) as shown in Table 3.1. Andrea Achilli [4], developed PRO model to predict water flux and power density under specific conditions. The model was tested with a flat-sheet cellulose triacetate (CTA) FO membrane, various feed solution concentrations and draw solution concentrations from 0-5 and 20-60 g/L NaCl, respectively. The results showed that maximum power density of 2.7 and 5.1 W/m^2 were observed for 35 and 60 g/L NaCl draw solutions, respectively, at 970 kPa of hydraulic pressure. The effect of internal concentration polarization of CTA membrane substantially affected on power density. The effect of external concentration polarization of CTA membrane slightly affected on the osmotic pressure driving force. Optimal conditions of pressure retarded osmosis (PRO) process can be determined from mathematical model.

Because power output from PRO process is not maximum value, the study of thermodynamic analysis was interesting. It can be calculated theoretical power generation and evaluate power efficiency of system in term of power density. The theoretical power generation is the Gibbs free energy of mixing of two solutions that were different concentrations. Ngai Yin Yip et al [17] studied thermodynamic and energy efficiency analysis of PRO work extraction. Firstly, a reversible thermodynamic model for PRO was investigated and verified. The theoretical maximum extractable work in a reversible PRO process was to identify the Gibbs free energy of mixing. The highest extractable work from seawater as draw solution and river water as feed solution is 0.75 kW•h/m^3 while the Gibbs free energy of mixing was 0.81 kW•h/m^3 when thermodynamic efficiency analysis was 91.1%.

Until 2009, PRO process had only been studied in laboratory scale and no one had studied the feasibility of technology in commercial scale. In 2009, the first osmotic power plant prototype based on PRO process was finally opened by Statkraft company in Tofte, Norway. The plant prototype can be produced power density of 1 W/m^2 with 2000 m^2 of membrane area [18]. However, construction of PRO plant to power generation should be determined feasibility of technology as well as economic analysis.

Table 3.1 Transport properties of the reported TFC-PRO flat-sheet membranes and the HTI CTA membrane [3].

Membrane	A (10^{-9} m s^{-1}kPa^{-1})	B (10^{-7} m s^{-1})	S (μm)
TFC-1	2.78	0.50	-
TFC-2	2.22	0.30	-
TFC-3	14.72	5.55	600
TFC-4	2.77	-	-
TFC-5	2.20	-	-
TFC-6	1.52	-	-
TFC-7	1.19	-	-
TFC-8	11.39	4.83	150
TFC-9	7.86	1.22	273
HTI-TFC	6.92	1.08	564
HTI-CTA	1.83	1.20	790

CHAPTER 4

RESEARCH METHODOLOGY

4.1 Mathematical model for pressure retarded (PRO) process

A mathematical model is used to calculate the performance such as water flux (J_W) and power density (W) of PRO process. This model considers the effects of concentration polarizations which consist of internal concentration polarization (ICP) and external concentration polarization (ECP) in both support layer and dense layer (or active layer). Figure 4.1. presents salt concentration and osmotic pressure profiles in PRO process at the active layer facing the draw solution (seawater). The $C_{D,b}$ and $C_{F,b}$ are salt concentration of draw solution and feed solution at bulk layer (water resources), respectively [14, 19]. The salt concentration at interface layer between draw solution and active layer of membrane is $C_{D,m}$. The effect of external concentration polarization (ECP) enhances lower concentration of $C_{D,m}$ than concentration of draw solution due to the fact that dilution of feed solution affects on water flux (J_W) [14]. The internal concentration polarization (ICP) leads to accumulation of salts in the active layer when water from the feed solution transports through the membrane. Therefore, the salt concentration at interface between support layer and active layer is higher than the bulk layer of the feed solution ($C_{F,m}$).

Water flux in PRO process when considering the effects of ECP and ICP can be calculated by equation 8 under the assumption that $C_{F,b}/C_{D,m}$ = $\pi_{F,b}/\pi_{D,m}$[14].

$$J_w = A\left[\pi_{D,b}\exp\left(\frac{-J_w}{k}\right)\frac{1-\frac{\pi_{F,b}}{\pi_{D,b}}\exp\left(J_wK\right)\exp\left(\frac{J_w}{K}\right)}{1+\frac{B}{J_w}\left[\exp\left(J_wK\right)-1\right]}-\Delta P\right] \tag{8}$$

$$\frac{\pi_{D,m}}{\pi_{D,b}} = \exp\left(\frac{-J_w}{K}\right) \tag{9}$$

$$K = \frac{t\tau}{D\varepsilon} \tag{10}$$

where k is mass transfer coefficient, K is solute resistivity, and $\pi_{D,b}$ are bulk osmotic pressure, ΔP is hydraulic pressure, and A and B are water permeability and salt permeability. The external concentration polarization is calculated by Equation 9 and the solute resistivity (K) is used to determine effects of internal concentration polarization which can be calculated by equation 10.

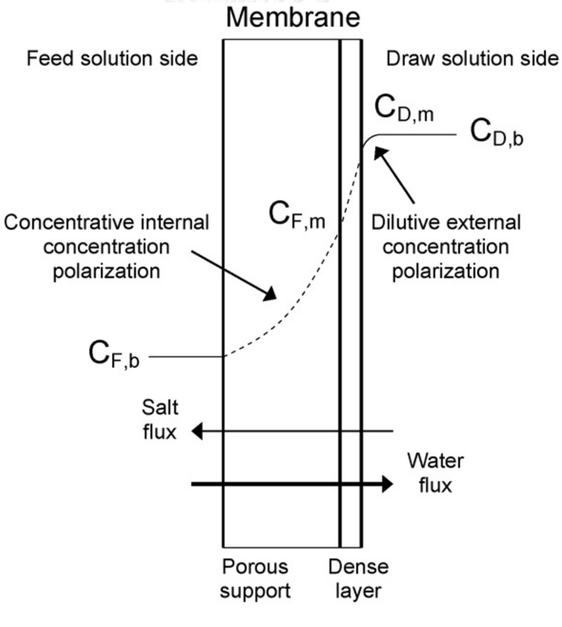

Figure 4.1 The salt concentration profiles in PRO process [4].

where D is diffusion coefficient and t, **τ** and **ε** are thickness, tortuosity and porosity of support layer membrane, respectively. The mass transfer coefficient (k) is calculated by equations 11 and 12.

$$k = \frac{ShD}{d_h} \tag{11}$$

$$Sh = 0.2\,\mathrm{Re}^{0.57}\,Sc^{0.4} \tag{12}$$

where S_h is Sherwood number, d_h is hydraulic diameter of the flow channel, Re is Reynolds number, and S_C is Schmidt number.

The power density (W) is a product of PRO process from water flux across membrane and input the hydraulic pressure which can be calculated by equation 13.

$$W=J_w\Delta P \tag{13}$$

4.2 Process condition

The performance of PRO process is investigated to find the optimal process conditions in term of maximum power density. The performance of PRO process depends on support layer morphology of membrane which should be high water permeability (A) and low salt permeability (B) [20]. A commercial CTA-FO membrane is a cellulose-triacetate (CTA) membrane which was reported in real situation, power density was 2.7 W/m^2 when fresh water and seawater are used as raw material. Therefore, a tradeoff between A and B must be optimized [21]. Both TFC-PRO membranes are tested in PRO process which is high water permeability and high power density equal to 10.0 W/m^2 and 12 W/m^2, respectively. So all membranes in Table 4.1 are selected in this work. All membranes are flat-sheet membranes in order to decrease effect of pressure drop of the system. The effect of concentration are studied from different water resources as shown in Table 4.2. Seawater which is higher salt concentration is represented as draw solution. While seawater, brackish water, waste water and river water are used as feed solution. The effects of feed flow rate which are varied from 1 to 10 L/min to find optimal flow rate of process. The conditions for simulation are presented in Table 4.3 by using Aspen Custom

Modeler. The PRO process are simulated under specific assumptions such as steady state and continuous system, neglected pressure drop, constant inlet hydraulic pressure, solution consisting of only water and NaCl, and constant temperature.

Table 4.1 Types of membrane.

Description	A ($\times 10^{-12}$ m^3 /m^2 s Pa)	B ($\times 10^{-7}$ m^3 /m^2 s)	t (μm)	Reference
1.Commercial CTA-FO	1.87	1.11	678	[8]
2.Lab TFC-PRO-1	16.14	2.44	349	[9]
3.Lab TFC-PRO-2	14.72	5.55	600	[9]

Table 4.2 The water resources[9].

Draw solution	Feed solution	Osmotic pressure different (bar)
Seawater (0.5M NaCl)	Brackish water (0.08M NaCl)	19.10
	Waste water (0.05M NaCl)	20.45
	River water (0.01M NaCl)	22.28

Table 4.3 Conditions for simulation.

Parameters	Value
Temperature, (^{o}C)	25
Membrane length, L (m)	1
The hydraulic diameter of the flow channel, d_h (m)	9.46×10^{-4}
Salt diffusion coefficient, D (m^2/s)	1.51×10^{-9}

A computer program based in Aspen custom modeler was developed as described in Figure 4.2.

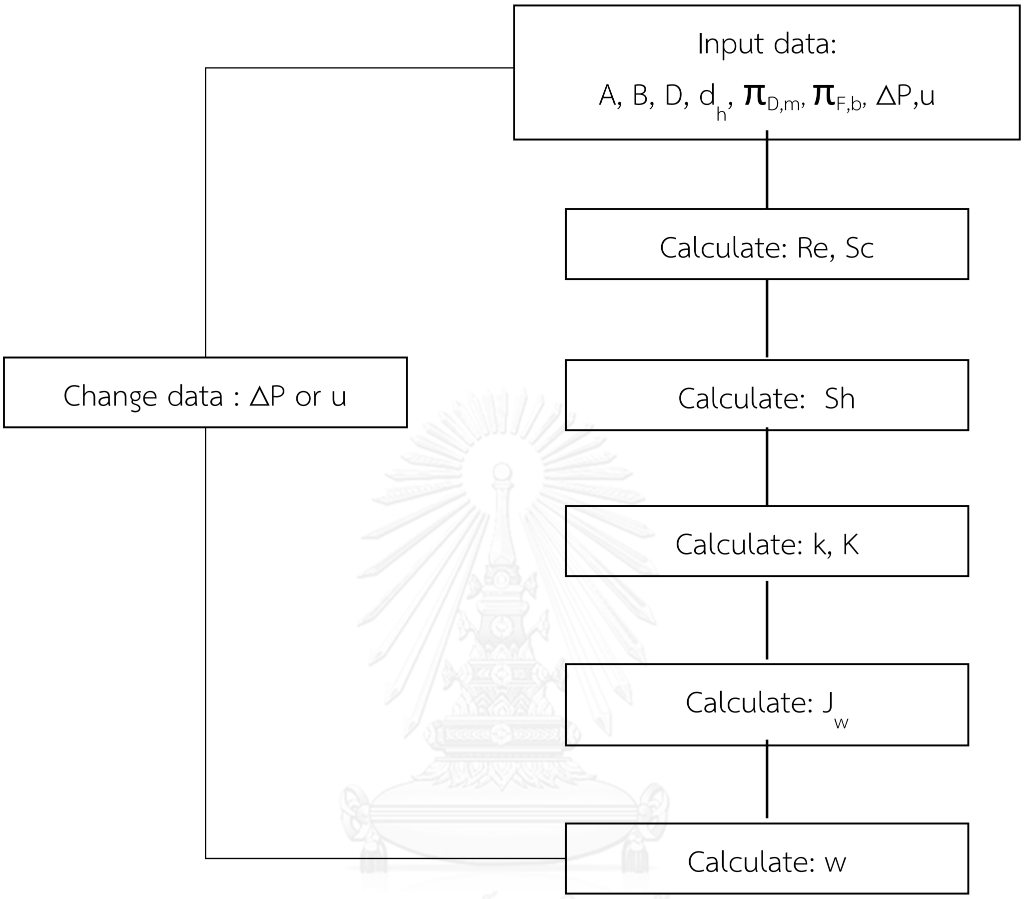

Figure 4.2 Flow chart used to solve the PRO equation.

CHAPTER 5

RESULTS AND DISCUSSIONS

The pressure retarded osmosis (PRO) process studied the mechanism of system in power generation which is produced from different of salinity of seawater and river water. Next, mathematical model was validated with experimental data from the literature reviews as shown in Section 5.1. Then section 5.2 showed the effects of parameters such as feed flow rate, water resource, and types of membrane by varying parameters to find the best condition in term of the highest power density. Then, the efficiency of PRO process was repeated by using the best condition in Section 5.3 from thermodynamic analysis method. The thermodynamic analysis was compared actual and theoretical power density. In the final section, the PRO process was scaled up to industrial scale for practical application. Moreover, capital cost was evaluated to find the possibility in power plant construction and also to expand an alternative production of environmental friendly power.

5.1 Validation

The validation of mathematical model was necessary to confirm feasibility of mathematical model which was selected for pressure retarded osmosis (PRO) process. A mathematical model including effect of concentration polarizations was used to calculate water flux (J_W) and power density (W) of PRO process. The simulation of PRO process was validated according to Andrea Achilli et al. [7]. Three feed solution that is 0, 0.04 and 0.09 molar, draw solution of 0.6 molar and a flat-sheet cellulose triacetate (CTA) FO membrane were used for simulation of PRO process. Water flux and power density were presented on y-axis and various hydraulic pressure (ΔP) is on x-axis as presented in Figure 5.1. The dash line was the data obtained from Achilli et al. [7] and solid line was received from model validation. The maximum of power density from validation was 2.9, 2.3 and 1.8 W/m^2 with 0, 0.04 and 0.09 molar of feed solution concentration, respectively. The results showed a good agreement with those data reported by Achilli et al. [7]. Therefore, mathematical model was acceptable for simulation of PRO process in this work.

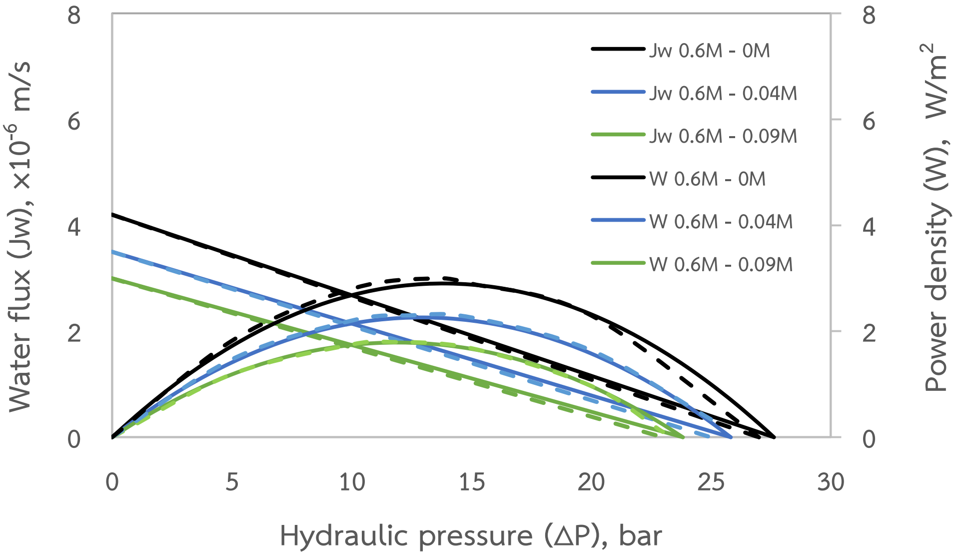

Figure 5.1 Validation results of water flux (Jw) and power density (W) as a function of hydraulic pressure.

5.2 Effect of parameter

Performance of PRO process in term of power density depended on several parameter such as feed flow rate, types of membrane and so on. In this work, the study on the effect of parameters including feed solution flow rate, draw solution flow rate, water resources, and types of membrane were varied in simulation model. The simulation results from different conditions were referred and explained in section 5.2.1 - 5.2.4.

5.2.1 Effect of feed flow rate

The important problem of diffusion of water from feed solution into draw solution was concentration polarization that included external and internal concentration polarization. The external concentration polarization (ECP) was caused by difference in salinity concentration at position of bulk phase and interface of draw solution side. The external concentration polarization (ECP) causing water difficult diffusion through membrane led to film layer at membrane surface. This film layer reduced mass transfer coefficient. According to equation 11, mass transfer coefficient depended on flow rate so the effect of flow rate was studied in this part.

The PRO process including two feed streams such as feed solution and draw solution were both studied. The feed and draw solution flow rate were varied from 1 to 10 L/min to reduce effect of concentration polarization. Both flow rate streams were increased from 1 to 10 L/min. The commercial CTA-FO membrane with 1 meter length was used for simulation. The feed and draw solutions were fed into the system, water from feed solution side permeates through membrane into another side. When various hydraulic pressures were applied on draw solution side then power was generated. The results showed that power density was increased from 1.29 to 2.15 W/m^2 when flow rate increased from 1 to 5 L/min. However, the power density was constant at flow rate above 5 L/min. Thus, suitable flow rate was 5 L/min because external concentration polarization is insignificant.

Next, flow rate of solutions should be studied to determine the dominate factor of performance of PRO process. The feed and draw solutions were waste water and seawater, respectively. The first flow rate was fixed while the other solution was varied; therefore, feed solution flow rate was varied from 1 to 10 L/min and draw solution flow rate was fixed at 5 L/min. Commercial CTA-FO membrane for PRO process was used in this process. The results showed in Figure 5.3. The primary y-axis was water flux (J_W) and power density (W) presented the secondary y-axis was a function of hydraulic pressure (ΔP) on x-axis. The feed solution flow rate hardly affected to water flux (J_W) and power density (W) which was increased flow rate from 1 to 10 L/min value. The results showed that power density were between 1.50 to 1.59 W/m^2 at hydraulic pressure of 10 bar. At 5 L/min of feed solution flow rate, increasing of draw solution flow rate from 1 to 10 L/min increased power density slightly from 1.36 up to 1.64 W/m^2 at hydraulic pressure of 10 bar as shown in Figure 5.4.

Maximum power density was obtained when hydraulic pressure (ΔP) equal to difference in osmotic pressure ($\Delta\pi$) according to theory. Thus, increasing of flow rate caused an decrease in external concentration polarization (ECP) resulting to an increase in water flux and power density. Moreover, flow rate of draw solution is an significant factor than feed solution.

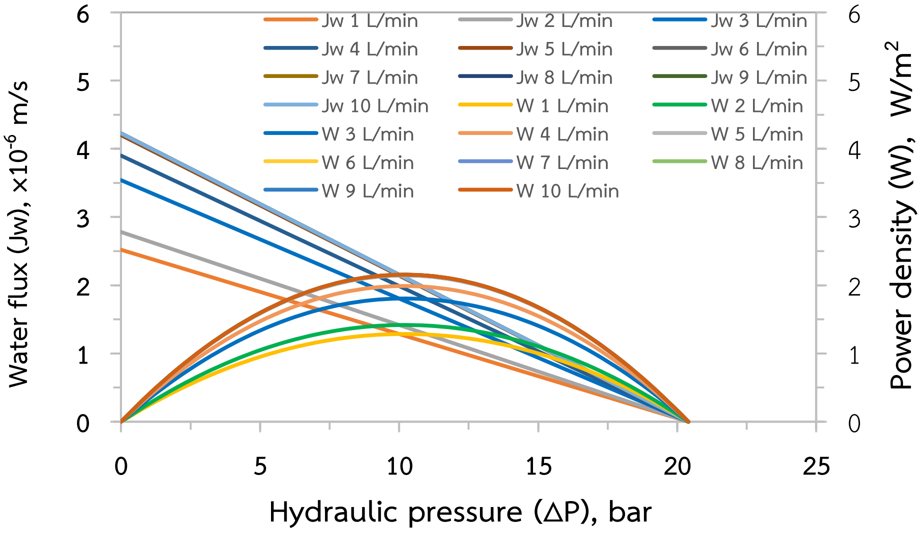

Figure 5.2 Effect of feed flow rate to water flux and power density with various feed solution and draw solution flow rate from 1 to 10 L/min, feed solution is waste water, draw solution is seawater and used Commercial CTA-FO membrane.

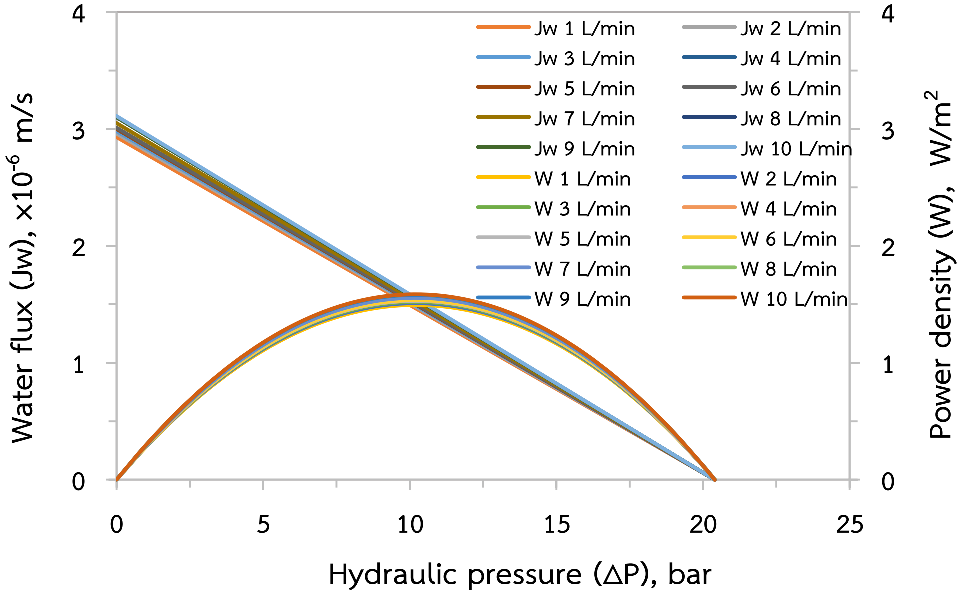

Figure 5.3 Effect of feed solution flow rate to water flux and power density with draw solution flow rate of 5 L/min, feed solution is waste water, draw solution is seawater and used Commercial CTA-FO membrane.

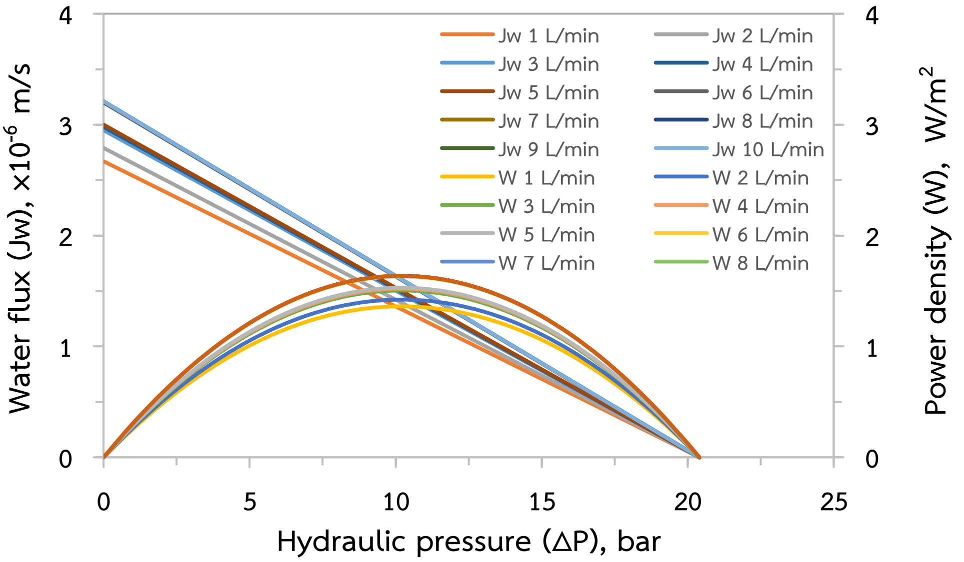

Figure 5.4 Effect of draw solution flow rate to water flux and power density with feed solution flow rate of 5 L/min, feed solution is waste water, draw solution is seawater and used Commercial CTA-FO membrane.

5.2.2 Effect of water resources and type of membranes

The effect of concentration of feed solution was studied. The concentration of feed solution affected on different osmotic pressure which was driving force of water through membrane. The high different osmotic pressure was obtained due to high different concentration between feed and draw solution. Hence, this section studied effect of concentration of feed solution with various water resources.

Generally, river water was used as feed solution while seawater was draw solution. However, utilization of low quality water resources including brackish water and waste water was considered in this work. Figure 5.5 showed impact of water resources presented in Table 4.2. The conditions for simulation were 5 L/min of draw solution and 1 L/min of feed solution. Types of membrane was commercial CTA-FO membrane with 1 meter length and various hydraulic pressure. The results showed that maximum power density was 1.88 W/m^2 when feed solution as river water (0.01M) and power density was 1.50 and 1.34 W/m^2 from waste water (0.05M) and brackish water (0.08M), respectively. From figure 5.6, Lab TFC-PRO-1 membrane was used. It was found that power density was 10.41, 9.10 and 7.74 W/m^2 when feed solution was river water (0.01M), waste water (0.05M) and blackish water (0.08M), respectively. From figure 5.7, Lab TFC-PRO-2 was used. The results showed that power density was 9.22, 7.99 and 7.10 W/m^2 when feed solution was river water (0.01M), waste water (0.05M) and blackish water (0.08M), respectively. From Figure 5.5 - 5.7, maximum density was reached when river water was used as raw material due to highest different osmotic pressure between feed solution and draw solution comparing other resources.

Next, internal concentration polarization (ICP) was studied by different types of membranes. The different properties such as thickness, tortuosity, porosity, water permeability and salt permeability affected to the solute resistivity for diffusion within the porous support layer (K) value according to equation 10 due to types of membrane. The internal concentration polarization depended on the solute resistivity for diffusion within the porous support layer (K) value. Three types of membranes from literatures including commercial CTA-FO membrane, Lab TFC-PRO-1 membrane and with Lab TFC-PRO-2 membrane were used as shown in Table 4.1. The performance of PRO process depended on support layer morphology of membrane which should be high water permeability (A) and low salt permeability (B) [7]. Power density of 2.7 W/m^2 from fresh water and seawater was reported for a commercial CTA-FO membrane, while a power density of 2.7 W/m^2 was observed for a cellulose-triacetate (CTA) membrane. Therefore, a tradeoff between A and B must be optimized [7]. Both Lab TFC-PRO membranes were tested in PRO process which was high water permeability; therefore, high power density equal to 10.0 W/m^2 and 12 W/m^2, respectively. So all membranes were selected in this work. Lab TFC-PRO-1 membrane offered maximum power density at 10.41 W/m^2 while minimum power density was obtained by using commercial CTA-FO membrane when feed solution was river water present in Figure 5.5 - 5.7. This is because value of water permeability was higher than other types of membrane and lower salt permeability. Thus, water flux can more pass through the membrane.

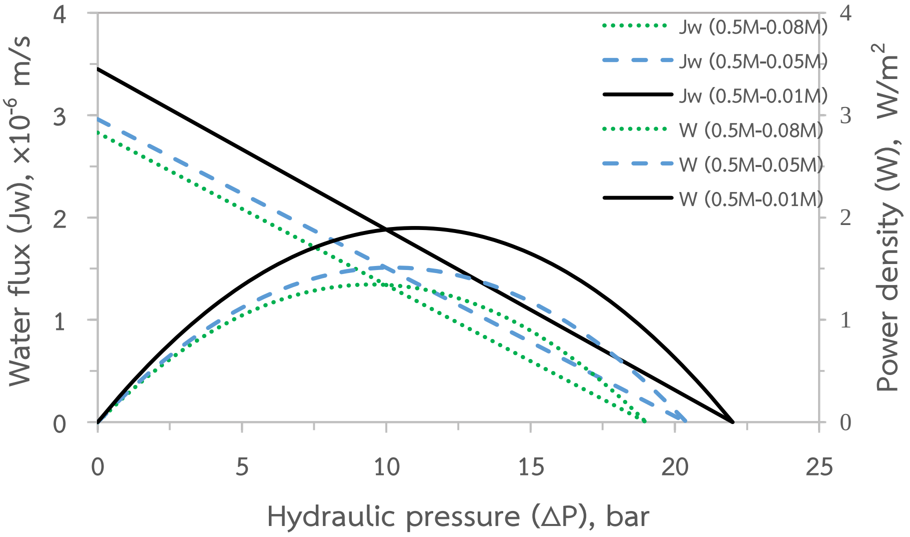

Figure 5.5 Effect of water resources to water flux and power density by feed solution is 1 L/min and draw solution flow rate is 5 L/min with Commercial CTA-FO membrane.

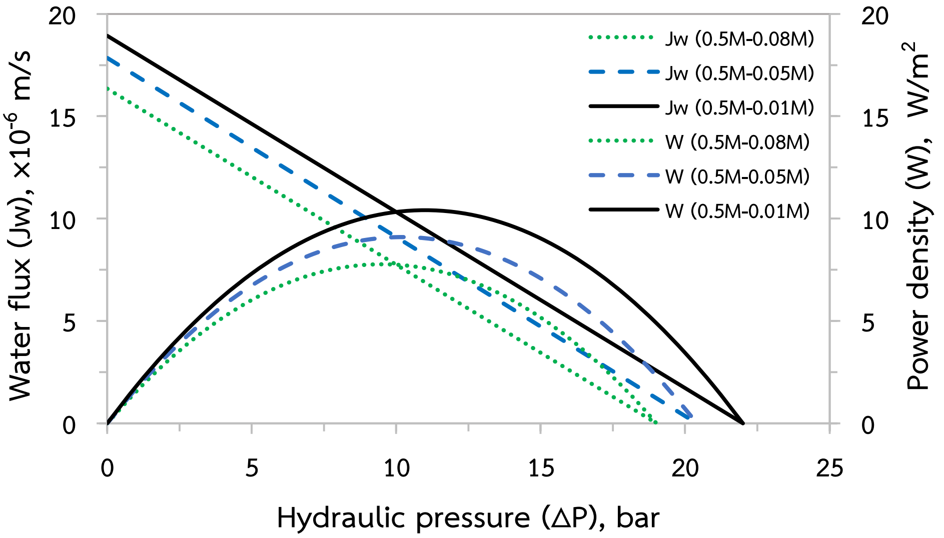

Figure 5.6 Effect of water resources to water flux and power density by feed solution is 1 L/min and draw solution flow rate is 5 L/min with Lab TFC-PRO-1 membrane.

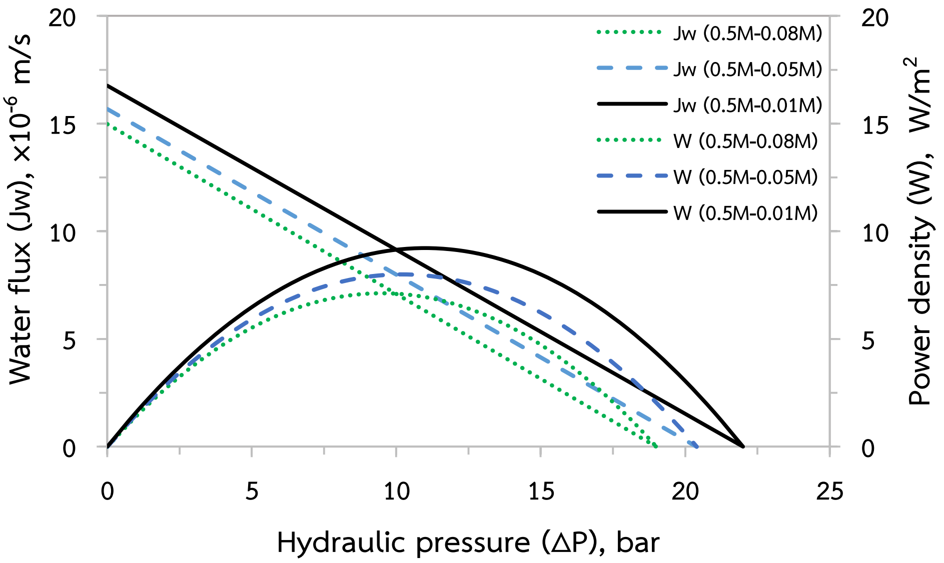

Figure 5.7 Effect of water resources to water flux and power density by feed solution is 1 L/min and draw solution flow rate is 5 L/min with Lab TFC-PRO-2 membrane.

5.3 Thermodynamic analysis

For pressure retarded osmosis (PRO) process for power generation, a semi-permeable membrane separated two solutions of different concentration. The different osmotic pressure was applied to drive water passing through membrane from the feed solution into draw solution. A hydraulic pressure less than different osmotic pressure was used on draw solution side and a turbine extracted power from expanding draw solution volume. In this section, the derivation of the theoretical maximum power and evaluation of efficiency of PRO process were presented. The efficiency was evaluated through comparison between actual and theoretical power.

When two solutions of different concentration were mixed, Gibbs free energy of mixing was released. The different Gibbs free energy between the final mixture and initial solutions gave the change in free energy of mixing that was the theoretical maximum power [17]. The change in free energy of mixing can be calculated according to equation 14.

$$-\frac{\Delta G_{mix}}{\nu RT} \approx \frac{c_M}{\phi}\ln(\gamma_{s,M} c_M) - c_F \ln(\gamma_{s,F} c_F) - \frac{(1-\phi)}{\phi}\ln(\gamma_{s,D} c_D) \qquad (14)$$

where ΔG_{mix} is the change in free energy of mixing, c_M, c_F, and c_D are molar concentration of mixing solution, feed solution, and draw solution respectively, $\gamma_{s,M}$, $\gamma_{s,F}$ and $\gamma_{s,D}$ are activity coefficient of salt in mixing, feed solution and draw solution respectively, ϕ is ratio of total moles (or volume) of the permeate to total moles (or volume) of the system, and ν is number of ions each electrolyte molecule dissociates into. The conditions were used to calculate of theoretical maximum power presented in Table 5.1. The activity coefficients of the initial solutions (feed and draw solutions) and mixture were approximated by linear interpolation of the data in Table A1 [17]. In this study, the change in free energy of mixing (ΔG_{mix}) as a function ratio of total moles (or volume) of the permeate to total moles (or volume) of the system (ϕ) was calculated which was shown in Figure 5.8.

Table 5.1 The parameters for calculation of theoretical maximum power.

Parameter	Seawater	River water	Waste water	Brackish water
1. Activity Coefficient, γ_s	0.679	0.903	0.819	0.789
2. Concentration, c (Molar)	0.5	0.01	0.05	0.08
3. Ratio of total moles (or volume) of the solution to total moles (or volume) of the system, ϕ	-	0.02	0.09	0.14
4. Temperature, T (^{o}C)	25	25	25	25
5. Feed flow rate, V (L/min)	5	1	1	1

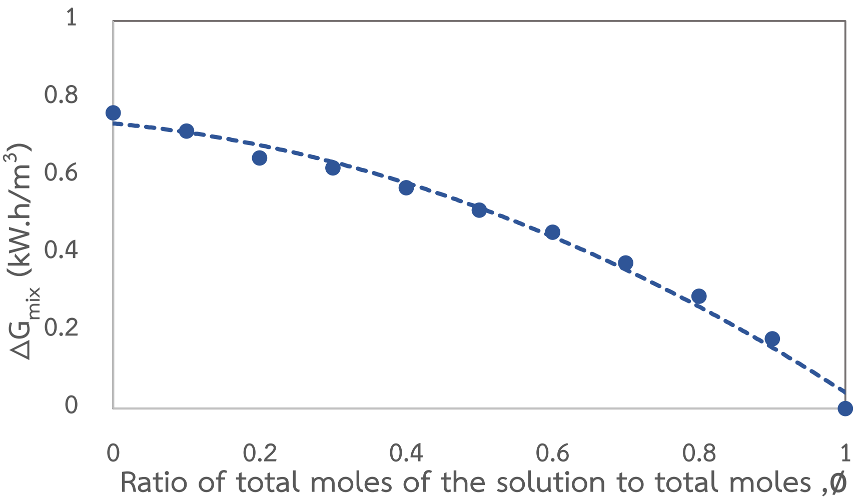

Figure 5.8 show the change in free energy of mixing (ΔG_{mix}) as a function of ratio of total moles of the solution to total moles (ϕ).

Table 5.2 The efficiency of thermodynamic efficiency of PRO process.

Type of membrane	Thermodynamic efficiency, η		
	River water	Waste water	Brackish water
1. Commercial CTA-FO	1.74%	1.4%	1.2%
2.Lab TFC-PRO-1	18.20%	15.29%	11.74%

Maximum change in free energy of mixing (ΔG_{mix}) was 0.763 kW•h/m^3 when ϕ value was zero. The change in free energy of mixing (ΔG_{mix}) decreased with an increase in ϕ and it was zero when ϕ equal to 1. Change in free energy of mixing (ΔG_{mix}) was determined in term of work from river water flowing into seawater. It was found that river water flow into the seawater 1 cubic meter can be produced energy of 2635 kJ. Next, the thermodynamic efficiency (η) was calculated according to equation 14 to evaluate efficiency of system and theoretical and actual power output were compared. The thermodynamic efficiency (η) used commercial CTA-FO membrane and Lab TFC-PRO-1 membrane. The results showed that thermodynamic efficiency using Lab TFC-PRO-1 membrane was maximum value with feed solution as river water as shown in Table 5.2. The minimum percentage of thermodynamic efficiency was 1.2% when seawater was considered as draw solution and brackish water as feed solution. On the other hand, the maximum percentage of thermodynamic efficiency was 18.20% when seawater was considered as draw solution and river water as draw solution.

5.4 Economic analysis

PRO process was scaled up to pilot scale under the best condition from Section 5.2. Commercial membrane from pilot plant was compared with the suitable membrane from this work in term of power generation. Net power output from the pilot plants was computed and capital cost of PRO process was evaluated in this section.

5.4.1The scale up of PRO process

Until 2009, PRO process had only been performed in laboratory scale and no one had studied the feasibility of the technology in industrial scale. In 2009, the first prototype of osmotic power plant based on PRO process was structured by Statkraft in Tofte, Norway. The prototype plant in Norway was equipped with 2000 m^2 of membranes and was reported power density of 1 W/m^2, meaning an overall power output of 2 kW [2]. A general sketch of the prototype power plant was shown in Figure 5.9. The plant included river water and seawater streams. The river water entered the plant at low pressure, then passed into a mechanical filtration system to remove impurities prior to entering the semipermeable membrane. While, seawater was pumped, filtered and sent into pressure exchanger before entering the semipermeable membrane. Due to different osmotic pressure between river water and seawater in membrane, the water from river water permeated side was divided into two streams, the first stream was diverted into a turbine for power generation and another stream was diverted to the pressure exchanger to increase pressure of the inlet seawater. River water flow rate was 1200 L/min and seawater flow rate was 780 L/min.

The best conditions from Section 5.2 were 1 L/min of feed solution flow rate and 5 L/min of draw solution flow rate, respectively. The maximum power density was obtained by using Lab TFC-PRO-1 membrane. The best conditions were used for scale up to pilot scale as shown in Table 5.3.

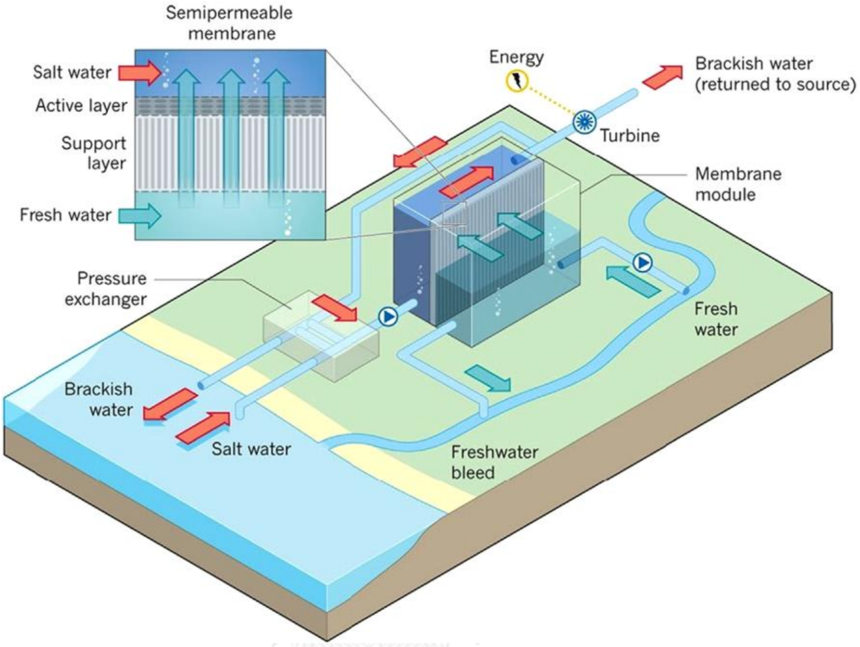

Figure 5.9 Schematic diagram of a PRO plant run on river water vs. seawater. Reprinted by permission from Macmillan Publishers Ltd:Nature [10].

Table 5.3 The conditions of pilot scale of PRO process.

Parameter	Seawater	River water	Waste water	Brackish water
1. Feed flow rate, V (L/min)	1200	240	240	240
2. Concentration, c (Molar)	0.5	0.01	0.05	0.08
4. Temperature, T (℃)	25	25	25	25
3. Total membrane area, m^2	2000			

Table 5.4 The simulation results of pilot sale of PRO process by using flat sheet cellulose acetate (commercial) membrane at best conditions.

Water resources	Power density (W/m^2)	Power (kW)
1. River water (0.01M)	0.98	1.96
2. Waste water (0.05M)	0.82	1.64
3. Brackish water (0.08M)	0.65	1.30

Table 5.5 The simulation results of pilot sale of PRO process by using Lab TFC-PRO-1 membrane at best conditions.

Water resources	Power density (W/m^2)	Power (kW)
1. River water (0.01M)	10.02	20.04
2. Waste water (0.05M)	8.22	16.44
3. Brackish water (0.08M)	6.19	12.38

The simulation results were compared in PRO pilot plant when commercial (flat sheet cellulose acetate) membrane with 1 meter of length and Lab TFC-PRO-1 membrane at feed flow rate of 240 L/min were used. It is found that power of 20.04 kW using Lab TFC-PRO-1 membrane was reported. This power was higher than flat sheet cellulose acetate membrane, as shown in Table 5.5. Therefore, this work showed higher performance than prototype plant up to 20 times. Power generation in prototype plant conditions and the conditions in this work were compared. It found that feed solution flow rate in this work was lower than prototype from 780 L/min to 240 L/min when power generation of both processes were closely value, presented in

Table 5.4. It implied that lower energy consumption was required at lower flow rate. However, size for pilot scale of the Lab TFC-PRO-1 membrane was still limited.

5.4.2 The net power from PRO power plant

5.4.1 Mass balance and energy balance

Mass balance of pressure retarded osmosis (PRO) process was determined to confirm reliability of system. Figure 5.10 show diagram mass balance of pressure retarded osmosis (PRO) process which red dash lines are material inlet and outlet from process.

$$\frac{dm}{dt} + \dot{m}_{inlet} + \dot{m}_{outlet} = 0 \qquad (15)$$

Where $\frac{dm}{dt}$ is rate of change of mass, $\dot{m}_{inlet}$ is inlet mass flow rate and $\dot{m}_{outlet}$ is outlet mass flow rate. Because PRO process is steady-state process so rate of change of mass ($\frac{dm}{dt}$) equal to zero. In Figure 5.10, inlet mass flow rate consist of red dash lines 1 and 2 and outlet mass flow rate consist of red dash lines 3, 4 and 5 were used to calculate mass balance of process show in equation 16. When mass balance was calculate according to equation 16 found that inlet mass flow rate equal to outlet mass flow rate.

$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3 + \dot{m}_4 + \dot{m}_5 \qquad (16)$$

Energy balance of PRO process was determined under steady-state process according to equation 17.

$$\Delta H + \frac{\Delta u^2}{2} + g\Delta z = Q + W_s \qquad (17)$$

Where ΔH is enthalpy change, $\frac{\Delta u^2}{2}$ is kinetic energy, $g\Delta z$ is potential energy, Q is heat and W_S is shaft work of flow process. PRO process can be neglected term of enthalpy change (ΔH), kinetic energy ($\frac{\Delta u^2}{2}$), potential energy ($g\Delta z$) and heat (Q) so energy balance is shaft work (W_S) of zero. In PRO process has 4 equipment for generation shaft work (W_S) such as high pressure pump, low pressure pump, pressure exchanger and turbine which high pressure pump, low pressure pump required work for operation but pressure exchanger and turbine generated work. Therefor, energy balance can be used to determine net power of PRO process according to equation 18.

$$\text{Net power} = \text{power generation} - \text{power consumption} \tag{18}$$

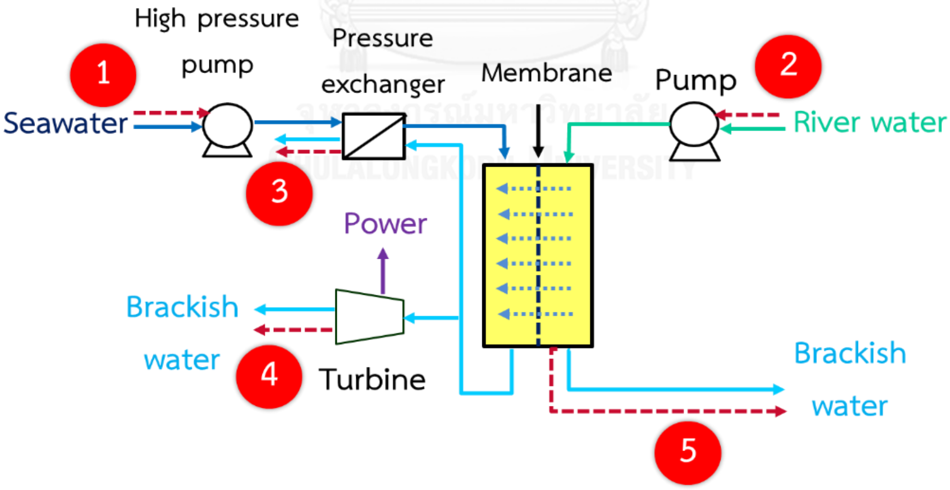

Figure 5.10 show mass balance of pressure retarded osmosis process.

5.4.1 Net power

PRO process consisted of feed solution and draw solution streams for power generation. Low pressure feed pump and high pressure feed pump were required for feed and draw solution, respectively. Next, water stream across membrane into seawater side was divided into two streams. The first stream was sent to pressure exchanger for energy recovery while the second stream was sent to turbine for power generation. Net power of PRO process was difference of power generation and power consumption.

As mentioned previously, the major equipment of PRO process was high pressure pump, low pressure pump, pressure exchanger and turbine. The high pressure pump and low pressure pump were required for energy consumption. On the other hand, pressure exchanger was applied for energy recovery from exchange pressure between permeate stream and inlet stream of seawater. The turbine was used for power generation. In this Section, the efficiency of net power of PRO power plant by using all equipment was 80%. Table 5.6 presented net power from calculation of PRO pilot plant by using flat sheet cellulose acetate membrane. The results showed maximum net power about 1.53 kW by using river water as feed solution and seawater as draw solution. Similarly, net power of Lab TFC-PRO-1 membrane was higher than flat sheet cellulose acetate membrane in similar conditions as shown in Table 5.7. Although waste water and brackish water resulted in lower net power than river water. Waste water utilization is more useful for power generation.

Table 5.6 The net power of PRO pilot plant by using flat sheet cellulose acetate (commercial) membrane at best conditions.

Water resources	River water	Waste water	Brackish water
Power consumption, kW			
1. High pressure pump (η = 80%)	-0.096	-0.076	-0.061
2. Low pressure pump (η= 80%)	- 0.02	-0.017	-0.013
Power generation, kW			
3. Pressure exchanger	+ 0.075	+0.067	+ 0.049
4. Turbine (η= 80%)	+ 1.57	+ 1.31	+ 1.04
5. Net power (W), kW	1.53	1.28	1.02

Table 5.7 The net power of PRO pilot plant by using Lab TFC-PRO-1 membrane at best conditions.

Water resources	River water	Waste water	Brackish water
Power consumption, kW			
1. High pressure pump (η = 80%)	-0.096	-0.076	-0.061
2. Low pressure pump (η= 80%)	- 0.02	-0.017	-0.013
Power generation, kW			
3. Pressure exchanger	+ 0.079	+0.069	+ 0.052
4. Turbine (η= 80%)	+ 16.03	+ 13.15	+ 9.90
5. Net power (W), kW	15.99	13.13	9.88

5.4.3 The capital cost of PRO power plant

Undoubtedly, commercial osmotic power plants today would incur an extremely high capital cost because a large membrane area is required to overcome low power density. For example, assuming a cost per unit area of membrane of \$30 [22], the power density of 1 W/m^2 would be approximately \$600 million for a 20 MW capacity power plant. In addition, capital cost was large due to turbines, pumps, pressure exchangers and other equipment.

Major equipment of system includinging membrane, high pressure pump, low pressure pump, pressure exchanger and turbine was calculated to evaluate capital cost. A unit capital cost can be estimated through the following equation 19.

$$C_c = \frac{C_T}{W} \tag{19}$$

where C_c is the unit capital cost (\$/kW), C_T is the total cost of PRO power plant, and W is the net power of PRO power plant (kW). To study capital cost of system, we compared using commercial membrane and highest performance (Lab TFC-PRO-1) membrane in this work. Commercial membrane cost per unit area of membrane was \$20 while Lab TFC-PRO-1 membrane cost per unit area of membrane was \$92 [2]. The results from capital cost by using commercial membrane were shown in Table 5.8. It is found that total cost was about \$41,000. The unit capital cost of system was achieved from calculation about \$26,800, \$32,000 and \$40,000 kW^{-1} when feed solutions were river water, waste water and brackish water, respectively. For using Lab TFC-PRO-1 membrane, unit capital cost was reported about \$11,500, \$14,100 and \$18,700 kW^{-1} when feed solutions were river water, waste water and brackish water, respectively. From the results, capital cost was still high in case of high cost per unit area of membrane unless power generation was high.

The current power plants has several resources such as wind, natural gas, petroleum liquids, biomass, solar cell, hydro, and so on. Average construction cost of each power plants are shown in Figure 5.10. When cost of PRO power plants were compared, it is found that cost of PRO power plant is greatly higher than other plants due to cost of membranes. The PRO power plants is interesting technology for power generation which is friendly technology to environment. Therefore, membrane structure should be improved to decrease cost of membrane.

Table 5.8 The capital cost of PRO pilot plant by using flat sheet cellulose acetate (commercial) membrane.

Equipment	Cost ($)	Reference
1. Commercial membrane	40000	[10]
2. High pressure pump	24.11	[11]
3. Low pressure pump	13.73	[11]
4.Pressure exchanger	1000	[12]
5. Turbine	5.51	[11]
Total cost	41043.35	

Table 5.9 The capital cost of PRO pilot plant by using Lab TFC-PRO-1 membrane.

Equipment	Cost ($)	Referent
1. Lab TFC-PRO-1 membrane	184000	[10]
2. High pressure pump	24.11	[11]
3. Low pressure pump	13.73	[11]
4.Pressure exchanger	1000	[12]
5. Turbine	5.51	[11]
Total cost	185043.35	

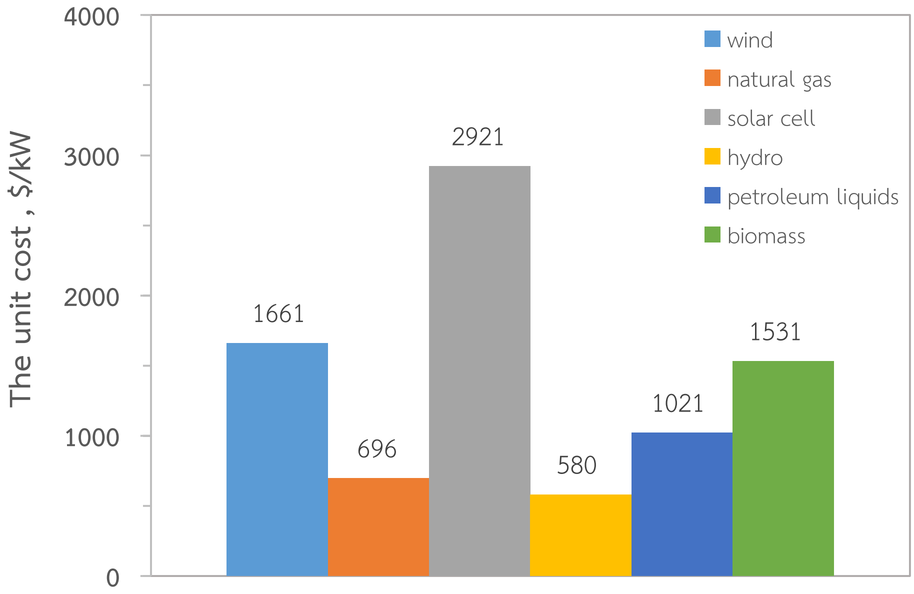

Figure 5.11 The average construction cost of different power plants from U.S. Energy Information Administration [13].

CHAPTER 6

CONCLUSION

The pressure retarded osmosis (PRO) process is studied from simulation using mathematical model; therefore, the mathematical model is validated with experimental data from literature reviews. Next, the effect of parameters such as feed flow rate, water resource, and types of membrane are determined the suitable condition in term of power density. Then, the efficiency of PRO process is repeated at the best condition by thermodynamic analysis method and compare actual and theoretical power density. In the final section, the PRO process is scaled up to pilot and capital cost is evaluated to find the possibility in power plant construction.

6.1 Effect of parameter

1. The best conditions for simulation of this work are feed flow rate of 1 L/min, draw solution flow rate of 5 L/min and Lab TFC-PRO-1 membrane offers maximum power density.
2. The effect of water resources, the river water shows maximum power density due to highest different osmotic pressure.

6.2 Thermodynamic analysis

1. The maximum of thermodynamic efficiency of PRO process is obtained with ratio of theoretical to actual values from simulation about 56% by using Lab TFC-PRO-1 membrane and feed solution as river water.
2. The thermodynamic efficiency value relates to power density.

6.3 Economic analysis

6.3.1 The scale up of PRO process

1. The maximum power is 20.04 kW by using Lab TFC-PRO-1 membrane and river water as feed flow rate.

2. Power density of commercial membrane is similar to prototype power plant in Norway under low feed solution flow rate.

6.3.2 The net power from PRO power plant

1. Lab TFC-PRO-1 membrane offers higher net power than commercial membrane.

2. The maximum net power from simulation of 15.99 kW that is higher than commercial membrane about 10 times is obtained in this work; however size of membrane is limited.

3. The low quality resources that is waste water and brackish water can be produced power.

6.3.3 The capital cost of PRO power plant

1. The unit capital cost of system was achieved from calculation about \$26,800, \$32,000 and \$40,000 kW^{-1} when feed solution as river water, waste water and brackish water, respectively and using commercial membrane.

2. Capital cost about \$11,500, \$14,100 and \$18,700 kW^{-1} when feed solution as river water, waste water and brackish water respectively is reported by using Lab TFC-PRO-1 membrane.

3. Although cost membrane is high but power density is obtained in high value the unit cost capital decreased too.

4. The unit capital cost of PRO power plant is greatly high cost when we compare with other technologies. The capital cost can be reduced by developing of membrane.

6.4.4 Recommendation

1. The pretreatment of feed solution and draw solution should be performed before solutions are sent to the membrane.
2. The permeate from process should be treatment before release into environment.
3. The other compositions in seawater should be concerned for real conditions.

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APPENDIX

Table A.1 Summary of the sodium chloride activity coefficients at different molar concentrations.

Molar concentration,c (mM)	Activity coefficient,γ (-)
0	1
1.51	0.957
6.03	0.920
13.6	0.888
24.1	0.860
37.7	0.835
54.4	0.813
74.1	0.794
94.6	0.778
190	0.735
238	0.720
286	0.710
383	0.693
480	0.681
579	0.673
678	0.667

A1. The calculation of power requirement of pump and turbine

For efficiency of pump can be calculated by Equation A1 where η is efficiency of pump, W is work requirement and W_s is work of isentropic.

$$\eta = \frac{W_s}{W} = \frac{\Delta H_s}{\Delta H} \tag{A1}$$

The efficiency of turbine can be calculated by Equation A2 where ηefficiency of turbine, W is is work requirement and W_s is work of isentropic.

$$\eta = \frac{W}{W_s} = \frac{\Delta H}{\Delta H_s} \qquad \text{(A2)}$$

The power requirement of pump and turbine can be calculated from integration of volume when pressure change through Equation A3 where P_1 and P_2 are initial and final pressure and V is volume.

$$\Delta W_s = \Delta H_s = \int_{P1}^{P2} V dP \qquad \text{(A3)}$$

A2. The calculation of power recovery by pressure exchanger

The pressure exchanger is used for recovery of power. The power recovery can be calculated from Equation A4-A5 [14].

$$P_{eq} = \frac{\pi_{HI}}{\frac{V_{HI}+\Delta V/w_{HI}}{V_{HI}}} \qquad \text{(A4)}$$

$$W = \int_0^{\Delta V} \frac{\pi_{HI}}{\frac{V_{HI}+\Delta V/w_{HI}}{V_{HI}}} d\Delta V = V_{HI}\pi_{HI}w_{HI} \ln(1 + \frac{\Delta V}{V_{HI}w_{HI}}) \qquad \text{(A5)}$$

Where

P_{ep}	is transmembrane pressure of pressure exchanger pressure
W	is power recovery
π	is Osmotic pressure
V	is Volume
ΔV	is Volume of water transferred across membrane
w	is Weight fraction of water
HI	is High osmotic pressure stream input

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