MODELING AND DESIGN OF OSMOTIC POWER PLANT: AN INVESTIGATION ON OPERATING FACTORS

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CERTIFICATION OF APPROVAL

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Approved by,

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgments, and that the original work contained herein has not been undertaken or done by unspecified sources or persons.

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Abstract

Worldwide energy consumption has been profoundly reliant on fossil fuels which cause extreme environmental change therefore the investigation of new technologies to create effective sustainable energy source plays a significant role on the planet. The more the population rise in Malaysia, the more demand for electricity increases. Since fossil fuels are rampantly exploited to depletion in Malaysia, thereby looking into the need for alternative resources is vital. To diminish the dependency on fossil fuel resources, Pressure Retarded Osmosis (PRO) is an encouraging contender by utilising energy from the salinity gradient between fresh water and seawater. According to the economic expansion of membrane technologies and recent improvements in the technology, PRO has possibly sustainable preference and has been actively conducted demonstrations from lab-scale to pilot-scale. For instance, a pilot plant has constructed in StatKraft, Norway where is the first PRO in the world in 2009, and PRO-hybrid pilot plants are under construction. In any case, in spite of this expanding consideration and the quick progressions of the PRO process, before PRO reaches the commercial level there are few confront however persist. Therefore, an effort has been taken to modeling and design a new osmotic power plant to investigate the operating factors. An investigation is carried out to design and model a new pressure retarded osmosis with its operating parameters. In this project, a complete explanation was described of the power station which appropriates to optimise the power generation following to system parameters. Besides, improving the PRO module designs is regarded to have a vital value suitable to the low module performance equated the membrane performance and high possibilities of design alteration to determine incompetent PRO modules. Therefore, as an approach to increase the performance of PRO systems, a dual stage pressure retarded osmosis (DSPRO) modules is proposed and investigated in this project. After that, a total power density achieved for the proposed DSPRO system was up to 56.168 W/m^2. Lastly, using DSPRO systems and increasing membrane modules up to a limited extent can dramatically improve the power density of the system for the effectively the same membrane area.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Energy is essential not only to our daily life but agriculture, transportation, telecommunication and industrial activities that influence economic growth. Malaysia possesses a good mix of energy resources such as oil, natural gas, coal and renewable energies a say as biomass, solar and hydro (Shafie et al., 2011). Malaysia is a country where depends on fossil fuel resources for the transportation and industry sector. In Malaysia, renewable energy sources becoming likable for sustainable energy development. This is due to renewable sources of energy are abundant in Malaysia, the significant ones are biomass and solar. Renewable energy also plays a vital role in reducing pollution and carbon emission caused by the usage of fossil fuels as energy sources(Chou et al., 2013)

With current rapid economic development, Malaysia needs more resources to support industrial development, enhance the productivity of capital, labor and other factors towards production. In Malaysia, the electricity sector is dependent on fossil fuel resources.

Over the past decade, Malaysia's population and development growth have resulted in significant huge usage of electricity. The demand for energy was 19,845 MW compared to 10 years which the demand for electricity was just 16,132 MW during 2014 in Malaysia (*Malaysian Economy in Figures | Unit Perancang Ekonomi, Jabatan Perdana Menteri*, 2020). According to Malaysia's Energy Commission 2019, August 2019 recorded a peak at 18,338MW, an increase of 3.1% (from 17,790 MW). This was contributed to by hot weather and high electric consumption by industrial activities. Major consumers were industry (40%), commercial (35%) domestic (23%) with 2% coming mainly from mining, public lighting and agriculture.

Mainly in Peninsular Malaysia, the high-demanded centers are dealing with shortages of electricity resources and want for larger generation capacity was impending. In Malaysia, electricity source is dependent on fossil fuel sources. During 2009, about 94.5% of fossil fuels such as coal, fuel oil and natural gas were used to generate electricity. The remaining electricity, 5.5% was generated by hydroelectric (Pusat Tenaga Malaysia, 2008 as cited in Shafie et al., 2011). The depletion of fossil fuels will make Malaysia lookout for alternative sources of renewable energy to sustain its development. Producing clean and sustainable energies is important to countermeasure the disadvantages of fossil fuels including carbon footprint and drastic climate change.

The government is keen to promote green technology usage to act as a catalyst for economic growth in the new economic model (*PaperTu | Malaysia Sustainable Cities*, 2020). This was emphasized as efforts in the utilization of renewable energy (RE) resources and efficient use of energy were vastly promoted.

There is an alternative yet an interesting source of renewable energy called "Blue Energy" or better known as salinity gradient power that has yet to be applied to its full potential. Salinity gradient power is based on salt concentration in saltwater and freshwater to generate energy (Bujang et al., 2016).

Energy generated between salt and freshwaters by using density gradient is a new idea proposed in the field of renewable energies. Osmotic power or salinity gradient power is a new form of renewable energy that can be obtained from the salinity difference between freshwater (river) and saltwater (sea). The osmotic power generation eliminates CO_2 emissions (Skilhagen et al., 2008).

1.2 PROBLEM STATEMENT

Fossil fuels are rampantly exploited to depletion owing to great electricity demand which thereby probes the need for alternative resources. Therefore, researchers have shown keen interest in harvesting energy from renewable sources and seawater in this regard, represents a virtually infinite resource for energy extraction. This has led to a renewed interest in adopting membrane technologies for harvesting energy and water treatment. The CO_2 emissions are increasing day by day as the usage of fossil fuels as energy sources increasing as well. Pressure Retarded Osmosis (PRO) has been a point of talk among scientists since the 1970s. However, the power generation capacity of a PRO system has still been a question mark on economic grounds during the scaling up of the process as existing PRO systems today. In earlier studies, the membrane used before had lower water permeability factor (A) and the power density is about 5 W/m^2 which are necessarily need to improve to create energy extensively. It is commercially available but needs a huge scope of the investigation. However, with advancements many factors like better membranes, multiple stages have been included to improve the execution and operation parameters. Therefore, as an approach to increase the performance of PRO systems, a dual stage PRO modules is proposed and investigated in this project.

1.3 OBJECTIVES

The aim of this project is:

1) To design a new pressure retarded osmosis with its operating parameters.

2) To model an osmotic power generation through dual-staging of PRO modules.

1.4 SCOPE OF STUDY

The focus of this project is to design and modeling an osmotic power plant with a dual-stage PRO plant with the same membrane area. However, this project is subjected to the following scopes:

1) To investigate the operating factor of new pressure retarded osmosis.
2) By using the osmosis transmission equation between freshwater and saline water, mass transfer across PRO membranes and the necessary mathematical equation has to progress to modeling and identify the operating factor.

CHAPTER 2

LITERATURE REVIEW

2.1 BLUE ENERGY

We are in need of more sustainable energies to reduce carbon dioxide emission, reducing pollution and usage of fossil fuel in the total global energy consumption(Ellabban et al., 2014). In order to fulfill the demand of the energy used by our society, it is vital to harvest clean energy from the environment for the survival and sustainable development of our civilization(Khan & Bhuyan, 2019). Some of the technologies that has gained traction recently are solar,wind and geothermal energy which are renewable resources which can provide sustainability. Ocean consists of 70% of the earth's surface and there is a remarkably abundant water resource. Ocean energy is regarded as a key renewable and clean energy source, which has been estimated to be totally over 75 TW globally (Ellabban et al., 2014). Ocean energy is categorised in five specific forms, such as tidal energy, water wave energy, ocean current energy, temperature gradient energy, and salinity gradient energy (Khan & Bhuyan, 2019). Salinity energy collected as the salinity diversity between seawater and freshwater is another enormous scope sustainable power source that can be used.When the river water streams into the ocean, unconstrained and irreversible merger of freshwater and seawater happens, prompting the expansion of entropy of the framework. Thermal energy of liquids can change over into electrical energy if the entropy transformation be utilized (Ellabban et al., 2014).

The salinity potential energy resource has the worldwide potential to produce around 2.42.6 TW, (all river effluents combined), which is equivalent to our current global electricity consumption . (Ortega et al., 2014). Since the 1950's, a so called "blue energy" has been recognized as a renewable energy source, which is the exploitation of the free energy stored in the salinity difference between freshwater and saltwater. It is possible to introduce a suitable device to harness energy in the salinity difference through new techniques such as electrochemical capacitor and Nano-fluidic diffusion techniques (Lee et al., 2020).

2.2 OSMOTIC POWER PLANT

Osmosis is a natural process and for centuries it has been known that when salt water and fresh water are portioned in two chambers separated by a semi-permeable membrane, made for example of a biological membrane, freshwater will permeate through the membrane. A large quantity of energy is released when the river water meets salty ocean water. Only a little significant increase in water temperature is observed as a result of mixing these different waters, therefore it is a challenge to harvest this energy (Skilhagen, 2010). Osmotic power is a new energy conversion concept even though osmosis was widely known. In the 80s & 90s, membrane technology was introduced successfully in many industrial applications and efficient semi-permeable membranes became accessible. In the late 90s efficient transfer of mechanical energy between fluids was also made possible (Skilhagen et al., 2008). Over the last decade of actively studied and most widely used salinity power generation technologies are battery mixing (BattMix), capacitive mixing (CapMix), reverse electrodialysis (RED), pressure retarded osmosis (PRO) and hydrogel swelling (Straub et al., 2016).

In the last couple of decades, PRO was identified as a viable concept to convert osmotic energy into electricity. This potential idea presented a worldwide electricity production of more than 1600 TWh per year – equivalent to half the annual power generation in the European Union. In PRO, chemical energies are transferred as pressure. The naturally happening osmosis is where water keen to set homogenous salinity of liquids, this is what osmotic power is based on PRO is understood where semipermeable membrane controls molecules to pass through; from a low salinity solution to a highly concentrated salinity solution as shown below in Figure 2.1.

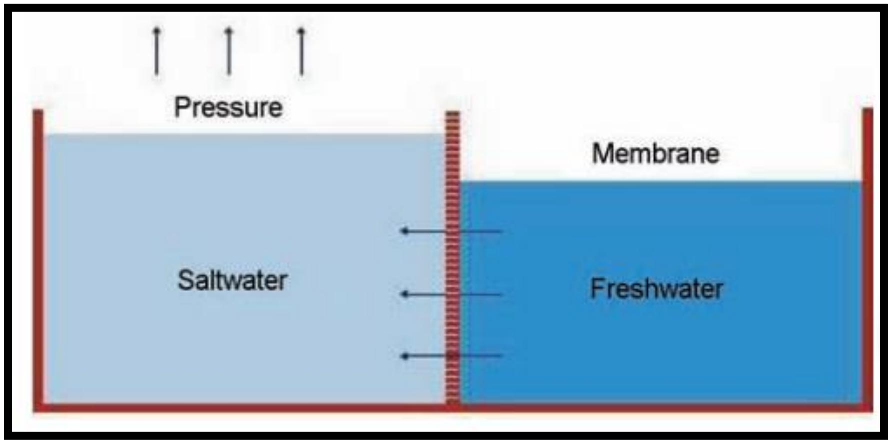

Figure 2.1: The standard of pressure retarded osmosis [(Source: Skilhagen, 2010)

A specific permeable membrane only allows diluted water to pass through, that too by separating salt and freshwater plus generating a strong force. With this method, osmotic pressure can be generated by the transfer of freshwater to the seawater. Osmotic pressure created here is estimated to be 24-26 bar. This pressure value can change depending on the salinity presence to seawater (Skilhagen, 2010). Figure 2.2 a illustrates precise PRO system filtered seawater and freshwater.

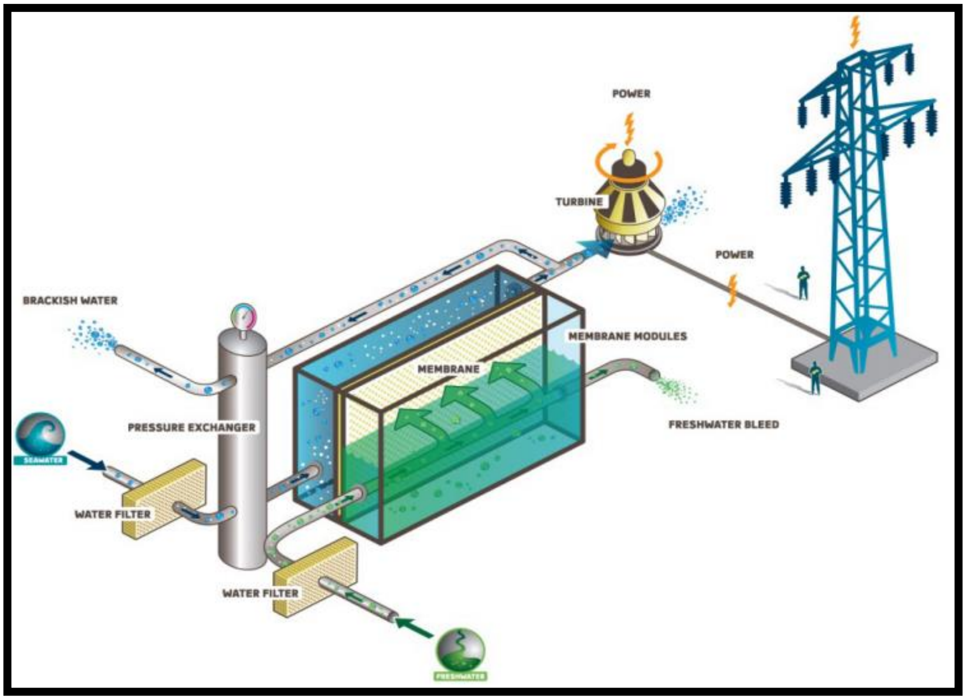

Figure 2.2: The standard of osmotic power plant [Source: (Skilhagen, 2010)]

The osmotic power plant exploits the energy product of mixing water with dissimilar salt gradients. In the development the water with low salt substance moves through the membrane to the side with the higher salt concentration and creates added pressure due to osmotic force Seawater pre-pressured approximately half of the osmotic pressure at 12-14 bars before entering the membrane modules. On the other hand, freshwater jumps through the membrane into the pre-pressured seawater in the module. Two types of streams is the outcome of this pressurized diluted seawater. About 33% of this pressurized sea water used to drive the hydropower turbine while the others flow through a pressure exchanger to continue pressuring incoming seawater. Brackish water is the name for the disposed water from the outlet back to the sea. Eventually, the greater the salinity gradient, the more pressure will be produced. Likewise, the more water enters, the more power can be generated (Skilhagen, 2010).

2.3 ADVANTAGES OF OSMOTIC POWER PLANT

There is no pollution trace recorded from osmotic power plant. It is pollution free & renewable energy that is vastly available. This process produces no emissions that could contribute impact to the environment. Excellent environmental performance with no carbon emission makes this process qualify for top most notable green energy production. Even urban city area can be a promising site for osmotic power plant generation without affecting any further congestion or massive break and build. This is possible due the rivers that run into ocean will have to pass through these developed cities, therefore utilizing it much easier than initially viewed. To further support the idea, plants can be established fully in the underground, not disturbed by external factors. It is likely that osmotic power will be a promising sector to invest, research and develop in the near future. This would likewise stand for a new appealing business possibility for both the commercial power organizations and the technology providers (Skilhagen, 2010).

The energy produced is clean and nonpolluting therefore there is no carbon footprints during its operation or any other byproducts released and produces no greenhouse gases or likewise waste. Osmotic power plant is a renewable energy that will contribute to the reduction the over reliance on the burning of fossil fuels, so the electricity supply is constant and efficient. Once osmotic power plant built, the energy is free because it is generated from the ocean's power. It needs no fuel. This can delay the depletion of fossil fuel in Malaysia. Furthermore, osmotic power plant produces electricity reliability and it is also cost efficient in terms of maintenance. A PRO plant is expected to be in production for 75 to 100 years. Besides that the uses an abundant, inexpensive fuel source (water) to generate power (Adokar et al., 2013).

2.4 PRESSURE RETARDED OSMOSIS

In PRO procedures, a layer is set between the feed and draw arrangements, utilizing the fixation contrast to osmotically drive water saturation from the feed to the draw stream. The draw stream is then precisely pressurised to produce hydraulic power that in the end works hydro turbines to create power (Straub et al., 2016). Pressure Retarded Osmosis (PRO) is broadly known to have a higher power density and proficiency contrasted with other salinity energy. In a case study Yip and Elimelech demonstrated that PRO can accomplish 54–56% of effectiveness at 2.3–38 W/m^2, while Reverse Electro Dialysis (RED) has a moderately minor efficiency of 18–38% at 0.77–1.2 W/m^2 (Yip & Elimelech, 2014). Even though PRO is equipped for desalination, its principle reason has generally been for generation of power, likewise with other film or membrane based processes of power generation (Helfer et al., 2014).Loeb originally proposed PRO in 1973, however it was not until the 2000s that it was reintroduced to membrane network, and from that point has been constantly evolved in both education and industry in endeavors to accomplish commercialization (Sarp et al., 2016). The most usage of the PRO procedure was the pilot plant built in 2009 by Statkraft, a Norwegian organisation of energy, for generation of power utilizing waterway water and seawater. Subsequent this pilot PRO plant, there has been a remarkable development to keep growing PRO, for example, the joint collaboration among Statkraft and Hydro-Quebec, a Canadian service organization and Nitto Denko/Hydranautics (*Statkraft and Hydro-Québec to Cooperate on Research and Development into Osmotic Power | Hydro-Québec*, 2019). Furthermore, PRO has been created as a hybrid with other desalination forms in endeavors to diminish the high energy utilization of Seawater Reverse Osmosis (SWRO) and Membrane distillation (MD), incorporating the Megaton venture in Japan (SWRO-PRO) (Saito et al., 2012) and GMVP in Korea (MD-PRO)(Han et al., 2015). A FO-PRO hybrid framework was likewise proposed, so as to address the extreme fouling issue when utilising wastewater effluent as feed (Cheng et al., 2018). The PRO researchers are slowly perceiving the natural impediments of the greatest thermodynamic energy extract able from blending seawater and river water. For instance, when 0.6 M and 0.015 M of NaCl solutions are accepted as the draw and feed concentration, the surmised salinities of river water and seawater, the greatest Gibbs free mixing energy is just 0.26 kWh/m^3 (Straub et al., 2016). Since energy sources, for example, pretreatment (0.1–0.4 kWh/m^3), pressurisation (0.05–0.1 kWh/m^3) and input (0.02–0.05 kWh/m^3) are required for PRO activity, such a little extract able energy makes the PRO researchers to question the principal acceptability of PRO (Lin et al., 2014). Other than that, there is concern with inefficient spacer and module plans. Various investigations have recorded that the current spacers accessible in the market are not fit for PRO activity, as they cause extreme membrane distortion and channel blockage (Kim & Elimelech, 2012), yet hardly few novel spacer structures for PRO or any choices have been accounted for to date. Besides, PRO module advancement stays in its earliest stages, and there have been no huge achievements regardless of the number of studies on PRO procedures and mechanisms (Yip & Elimelech, 2014). Finally, because of its high weight or pressure nature PRO has a realized extreme fouling propensity, which turns out to be progressively huge when wastewater is utilized as the feed (Yang et al., 2019). Nevertheless, the capability of PRO presently yet seem to be completely acknowledged, as every one of the above segments are in progress. In this way, there is a significant to reexamine the acceptability of PRO in a broad and opportune way (Lee et al., 2020).

2.5 PRO OPERATING FACTORS

There are many types of operating factors of Pressure Retarded Osmosis which relatively investigated by each component such as module modeling and design, membrane fabrication and hybrid processes (Lee et al., 2020).

2.5.1 Membranes

Based on structural features, membranes can be categorised into two. Symmetric and (2) asymmetric. There are two general membrane structures: (1) flat sheet membranes and (2) hollow-fiber membranes. As shown in Figure 2.3(A), flat-sheet membranes are usually arranged in the spiral-wound fundamentals. To provide mechanical strength and flow channel, a sandwich of flat-sheet membranes arranged to form cover where a spacer is enclosed between each membrane (Han et al., 2018). A central perforated collecting tube is wounded around by the membrane envelop. During operation, feed flows in the outer portion of the membrane operation while infused water rushes towards the module center and disposes through the central collecting tube. Besides that, both of the membrane have vary advantages and disadvantage such as pressure loss, packing density, specific power production costs, fouling cleaning ability and propensity (Sivertsen et al., 2012).

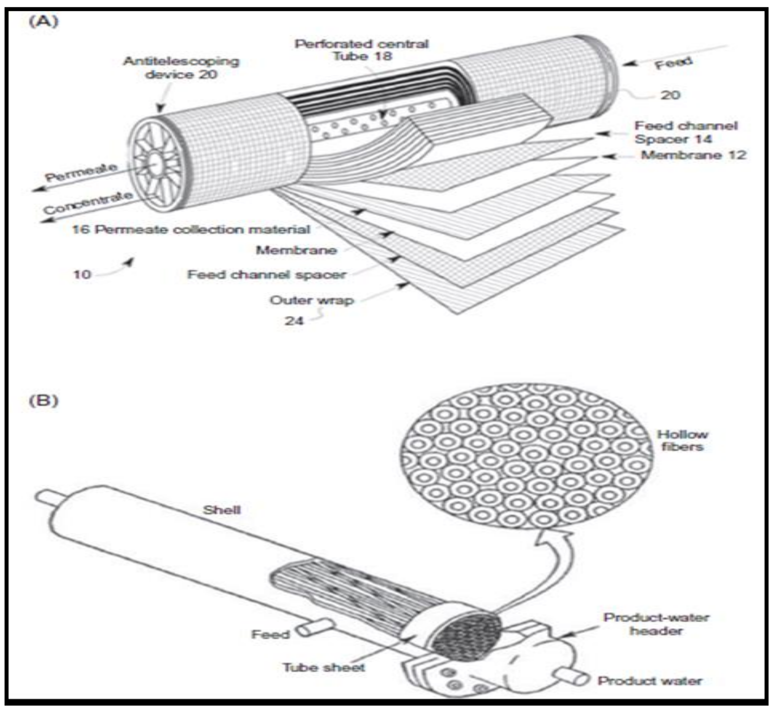

Figure 2.3: A typical spiral-wound flat-sheet membrane element (A) and hollow-fiber membrane module (B) (Cutaway sight of) [Source: (Han et al., 2018)].

2.5.1.1 Flat sheet membranes

Plate and casing modules can be straightforwardly applied on flat-sheet membrane as well as spiral-wound modules. Likewise, it is generally simple to make and control the help or specific layers. Along these lines, the investigation of PRO flat sheet membrane is significant so as to create business PRO membrane. Previously, PRO flat-sheet membrane was examined utilising business RO or FO membranes. In any case, RO membrane showed a low power density due to its dense support and thick layer (Lee et al., 2020). For instance, built up a thin film nanocomposite (TFN) PRO membrane utilizing a functionalized carbon nanotube (fCNT) composite polyethersulfone (PES) support with a chemically altered PA particular membrane. The force thickness of the created membrane was 110% higher than the perfect TFC membrane(Chou et al., 2013). The higher permeability membrane was innovated which the water permeability created 4.40 Lm−2h−1 bar−1(Lim et al., 2018). Flat sheet membrane are generally utilized in the winding injury components. The gathering comprises of a sandwich of flat sheet membrane to frame an envelope where a spacer is encased between every membrane to give mechanical strength and stream channel. The membrane envelope is twisted around a focal punctured gathering tube(Han et al., 2018).

2.5.2 Modules

Generally, membrane modules have widely used for PRO membranes which manufactured using cellulose triacetate (CTA), cellulose acetate (CA) and thin-film composite (TFC) membrane. Compare to CA or CTA, TFC membranes are convenient to adapt deliver support and particular layers have greater water flux. In this way, numerous researchers have concentrated PRO membranes utilising a TFC membrane (Lee et al., 2020).

2.5.3 Optimising of modules of the PRO process to Maximum Energy Extraction

Optimizing the hydraulic pressure in 4 components PRO framework is equivalent energy generation in the PRO framework is 0.404, 0.23, 0.12, and 0.038 kW h/m^3 for salinity gradient 5 M-0.6 M, 5M1.2 M, 1.2 M-0.02 M, and 0.6 M-0.02 M, respectively. Besides that, recent modeling investigations revealed that enhancing flow rate conditions greatly affects the PRO performance than hydraulic pressure; accordingly, this consideration likewise should be taken into account in module design optimization. Further, the energy output in the PRO procedure increased with expanding the quantity of the PRO module from 1 to 3 modules such as optimizing the feed solution flow rate, draw solution flow rate and hydraulic pressure. However, a slight improvement in the energy output was accomplished by including a fourth module (Chen et al., 2019)**.**

2.5.4 Optimisation, Simulation and Modelling a Pressure Retarded Osmosis Power station

Membrane modules, pressure exchanger and membrane modules are generally contained in PRO power plant (Di Michele et al., 2019).

2.5.4.1 Basic theory of PRO power plant

The pressure that would terminate the passage of feed solution across the semi permeable membrane if applied to the draw solution is called osmotic pressure. The osmotic pressure (π) of any arrangement can be determined utilizing the van't Hoff condition, as shown in below Eq. 2.1.

$$\pi = icRT \qquad \text{Eq. (2.1)}$$

c - molar concentration (mol L^{-1})

R- Universal gas constant (8.31441Nmmol^{-1} K^{-1})

T - absolute temperature (K)

i- number of osmotic active particles in the solution, [i=1+α(υ-1)]

α -degree of dissociation

v-the stoichiometric coefficient of dissociation reaction.The unit for π in is the kPa.

Water flux over the membrane in PRO procedures, Jw, is generally represented by the accompanying phenomenological relationship in Eq 2.2

$$Jw = Aw\,(\Delta\pi - \Delta P) \text{ Eq. (2.2)}$$

Jw is resolved as the result of the system permeability to water, Aw, and the net trans-membrane driving pressure, which is the net distinction between the osmotic pressure, Δπ, and the hydraulic pressure, ΔP.

The density of the power got from the PRO procedure, W, can be evaluated as the item from increasing the water flux by the water hydraulic pressure in Eq (2.3).

$$W = Jw \, \Delta P = Aw \, (\Delta\pi - \Delta P) \, \Delta P \text{ Eq (2.3)}$$

The power density of the membrane that is required to get a profitable PRO procedure was resolved to be between in the range of 4 and 6 W/m^2. The primary subordinate for equation as for ΔP expecting Aw as a consistent may determine the maximum value for W.

The membrane isn't totally impermeable to salt and a limited quantity will spill through the membrane. The salt flux Js over this position involve two segments: a diffusive part because of the salt concentration gradient, and a convective segment because of the mass stream induced by the water flux Jw.

$$Js = B.\Delta cm \text{ Eq(2.4)}$$

B- membrane salt permeability

Δc_m - concentration difference across the membrane

The outcome of this salt leakage is an accumulation of salt in the membrane's support layer and the development of a thin layer of concentrated solution at the interface between the support layer and the bulk feed solution.

2.6 Dual stage pressure retarded osmosis (DSPRO) and Advantages.

The dual stage pressure retarded osmosis is for power age utilising seawater as draw arrangement while the feed arrangement is a blend of fresh water, seawater is compressed and taken care of into the primary phase of PRO process while freshwater is the feed solution. The compressed seawater from the main stage, which has less concentration than seawater, is then taken care of into the second phase of PRO process for freshwater extraction from wastewater emanating feed arrangement. The benefits of the double stage PRO cycle are adaptability to deal with two feed arrangements requires an alternate degree of pretreatment. The primary stage and the second phase of the PRO cycle to decrease the pretreatment cost and film fouling. Reducing the effect of feed salinities on the exhibition of PRO interaction. The examination showed the capacity of dual-stage PRO interaction to reduce the impact of high feed salinities on the PRO process. High water penetrability thin film composite (TFC) layer is utilised in the primary phase of PRO cycle where freshwater is the feed arrangement while moderately high chlorine resilience cellulose triacetate (CTA) membrane is utilised in the second stage in which wastewater emanating is the feed arrangement. Hence it is appropriate for treating low fouling inclination feed arrangements like freshwater. The high fouling propensity feed arrangement, like wastewater profluent, requires CTA layer on account of its high resilience to chlorination during the cleaning cycle.

CHAPTER 3

METHODOLOGY

3.1 OVERVIEW OF RESEARCH

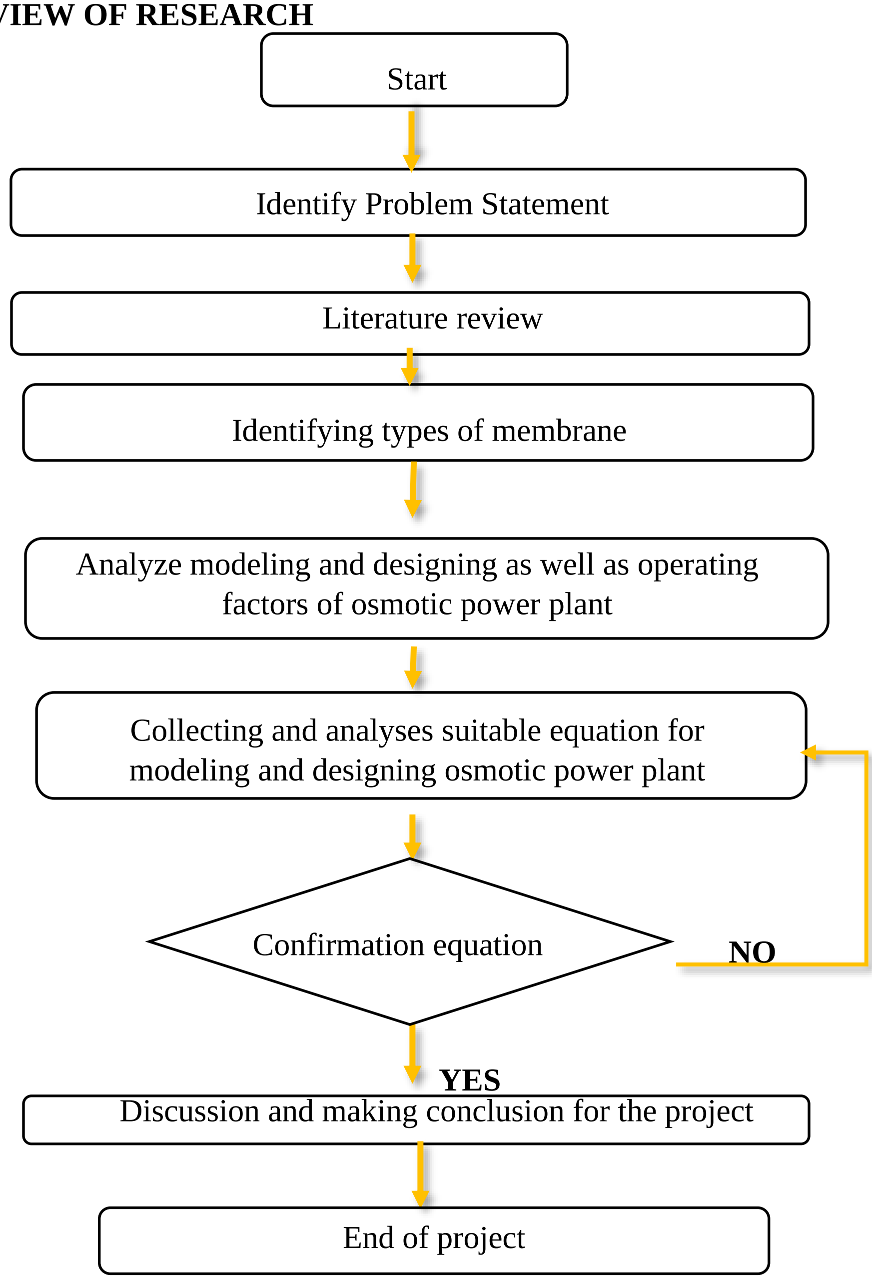

Figure3.1: Project Methodology

Figure 3.1 shows the project methodology employed in performing this project embraced of identifiying and investigate the operating factors and followed by analyses suitable equation for modeling and designing osmotic power plant.

3.2 RESEARCH METHODOLOGY

In this project, suitable osmotic processes and operating factors have been identified and analysed to design a new PRO system. A proper equations and calculations were investigated based on few research papers.

3.2.1 Basic Concept and Theory

Table 3.1: Proposed factors for designing a new osmotic power plant.

Parameters	**Proposed factors**
Osmotic membrane process	Dual Stage Pressure Retarded Osmosis
Osmotic membrane module	Cellulose Triacetate (CTA)
Membrane material	Polyether sulfone (PES) membrane
Membrane configurations	Flat Sheet Membrane

According to Table 3.1, these are the membrane parameters that have been taken into consideration to design an osmotic power plant. Dual-stage PRO system is being employed with a membrane configuration where flat sheet CTA membrane is the 1st stage followed by a similar CTA membrane as the 2nd stage. In a PRO process, power generation occurs due to a salinity gradient from saline solutions (rivers, sea, and wastewater), etc. hydraulic pressure is applied to pressurise the draw solution in order to convert the osmotic pressure to hydraulic pressure. Basically, in the PRO process by using the osmotic pressure from draw solution electricity can be produced and harvested. (Sarp et al., 2016).

3.2.2 A Schematic representation of the Dual Stage Pressure Retarded Osmosis (DSPRO)

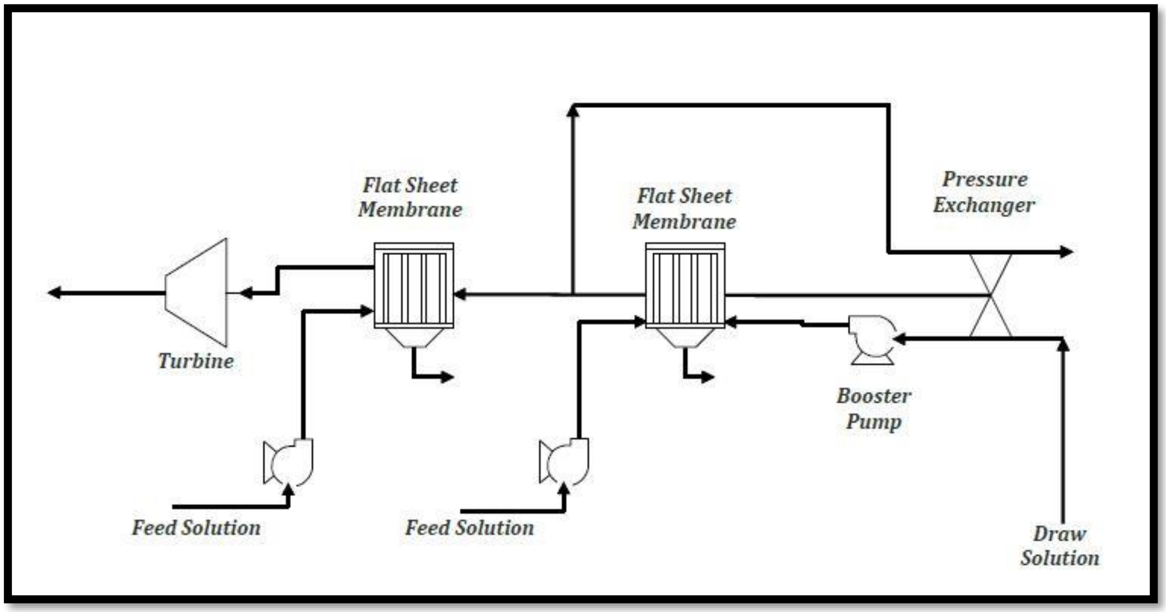

Figure 3.2: A Schematic representation of the Dual Stage Pressure Retarded Osmosis (DSPRO)

PRO power plants basically consist of the following components such as membrane modules, turbine for power generation, booster pumps and pressure exchanger. In this process two solutions of different concentrations i.e. river water (RW) with 5g/L NaCl as fresh feed solution and sea water (SW) with 70g/L NaCl as concentrated draw solution are fed into stage-1 which is composed of a flat sheet CTA semi permeable membrane with high solute rejection and water permeation. The draw solution is pressurized before entering the membrane. Due to the osmotic pressure gradient across the membrane, fresh water transports in the direction of the osmotic pressure gradients resulting in the dilution of the high-concentration solution. Some of the pressurized dilute draw solution after leaving from the first stage of the DPRO process is recycled back to a pressure exchanger to exchange pressure with the fresh draw solution while resulting diluted draw solution has a concentration of 50g/L NaCl and is being sent to the stage 2 of the system in order to exploit the remaining salinity gradient of the diluted draw solution in order to effectively raise the energy and economic efficiency of the system. DSPRO power plants do not need additional high pressure pumps on the draw solution as the already pressurised draw solution will be recycled in the second phase from the first stage PRO process and after leaving the membrane, the diluted draw solution is depressurised in a turbine system for power generation. as shown in Figure 3.2 (Altaee et al., 2018).

3.2.3 Proposed DSPRO Parameters and Operating Conditions

The experiment was performed with river water (RW) as the feed solution with 5 g/L NaCl concentration. However, seawater with 70 g/L NaCl was fed as the draw solution for the first stage which got diluted to 50 g/L and was sent to the second stage as draw feed. The temperature of the system was held constant at 27^{o}C and a pressure of 2400 kPa. For stage-1, hydraulic diameter (d_h) of the flow channel was 9.60×10^{-4}m and membrane length was 7.5×10^{-4} m. Water Permeability for the experiment was estimated to be 5.91×10^{-12} (m/Pa.s) and the Salt Permeability B was calculated to be 4.44×10^{-8} m/s.

For Stage 2, Membrane length and hydraulic diameter was taken the same as for membrane 1 and water permeability A and salt permeability B was estimated to be 7.19×10^{-13} (m/Pa.s) and 2.20×10^{-8} m/s, respectively (Matsuyama et al., 2021).

Table 3.2 Proposed conditions value of Stage-1 parameters

Operating conditions STAGE 1 (CTA) Flat sheet membrane	**Value**
Temperature (T)	27°C
Pressure (P)	2400000 Pa
Draw Channel hydraulic diameter (d_h)	9.60×10^{-4} m
Feed Concentration C_F	5 g/L

Draw Concentration C_D	70 g/L
Salt diffusion coefficient (D)	1.51×10^{-9}
Feed velocity (u_F)	0.133 m/s
Draw velocity (u_D)	0.133 m/s
Membrane length (L)	7.5×10^{-4} m
Water permeability (A)	5.91×10^{-12} (m/Pa.s)
Salt permeability (B)	4.44×10^{-8} m/s
Structure Parameter (S)	6.78×10^{-4} m

Table 3.3:Proposed condition values of Stage-2 parameters

Operating Conditions **STAGE-2 (CTA)** **Flat sheet membrane**	**Values**
Draw Channel hydraulic diameter (d_h)	9.60×10^{-4} m
Membrane Length	7.5×10^{-4} m
Feed Concentration C_F	5 g/L
Draw Concentration C_D	50 g/L
Salt diffusion coefficient (D)	1.51×10^{-9}
Feed velocity (u_F)	0.133 m/s

Draw velocity (u_D)	0.116 m/s
Water permeability (A)	7.19×10^{-12} (m/Pa.s)
Salt permeability (B)	2.20×10^{-8} m/s
Structure Parameter (S)	3.07×10^{-4} m

3.2.4 Evaluation of Flat Sheet Membrane Configuration

Evaluation of Flat Sheet Membrane Configuration:

The water permeate flux J_w is a function of the osmotic pressure difference $\Delta\pi$ across the membrane and the hydraulic pressure difference ΔP applied to the draw side. It is calculated by subtracting the hydraulic pressure from the osmotic pressure difference across the membrane (Jonathan Maisonneuve et al., 2014),

$$\boldsymbol{J_{w1} = A \times (\Delta\pi - \Delta P)} \qquad \text{Eq. (3.1)}$$

Where,

J_w (m/s) - Water permeate flux

A (m/Pa.s) – Membrane's water permeability

$\Delta\pi$ (Pa) – Osmotic pressure difference

ΔP (Pa) – Hydraulic pressure difference

Similarly for salt flux J_s,

$$\boldsymbol{J_{S1} = B(C_D - C_F)} \qquad \text{Eq. (3.1.1)}$$

Where,

J_s (m/s) - Salt permeate flux

B (m/ s) – Salt permeability

C_D (g/L) – Bulk salt concentration at sea water side

C_F (g/L) – Bulk salt concentration at fresh water side

Osmotic pressure difference (Δπ) is a crucial parameter and in fact is the main driving force behind the osmosis phenomenon and is defined as a function of concentration gradient Δc and temperature T, therefore we can employ vant' Hoff equation to get the osmotic pressure difference across a membrane (Jonathan Maisonneuve et al., 2014),

$$\boldsymbol{\Delta\pi = i_V \times R_g \times T \times \Delta c / M} \qquad \text{Eq. (3.2)}$$

Where,

R_g – Universal gas constant

For NaCl, i_v = 2 and M = 58.44 g/mol.

Resultantly the power density **w** which is defined as power per unit membrane surface area appeared across the membrane can be calculated by the following equation (Jonathan Maisonneuve et al., 2014),

$$\boldsymbol{w = J_w \times \Delta P} \qquad \text{Eq. (3.3)}$$

The hydraulic pressure difference developed across the membrane outlet ΔP_{out} is provided by,

$$\Delta P_{out} = \Delta P_{in} - (P_{D,drop} - P_{F,drop})$$

The feed and draw side pressure losses $P_{F,drop}$ and $P_{D,drop}$ can be described by (Schock G, Miquel A.,1987),

$$\mathbf{P_{drop}} = \int_{a}^{b} \frac{\mathbf{f \times p \times u^2}}{\mathbf{2 \times d_h}} \mathbf{dL} \qquad \text{Eq. (3.4)}$$

Where a and b are regarded as boundary conditions, i.e. a = 0 and b = L throughout the entire length of the membrane.

The friction factors f_F and f_D are regarded as function of Reynolds numbers Re_F and Re_D respectively (Hoek EMV, Allred J, Knoell T, Jeong BH., 2008),

$$\boldsymbol{f = 6.23 \times Re^{-0.3}} \qquad \text{Eq. (3.5)}$$

Where,

$$\boldsymbol{Re} = \frac{\boldsymbol{D \times u \times \rho}}{\boldsymbol{\mu}} \qquad \text{Eq. (3.6)}$$

D = d_h - Draw channel hydraulic diameter (m)

u – Cross flow velocity (m/s)

ρ – Density of the fluid (kg/m^3)

μ – Viscosity of the fluid (Pa.s)

The diffusion transfer coefficients for the feed and draw side K_F and K_D respectively, can be calculated by (Schock G, Miquel A., 1987),

$$\boldsymbol{K = 3 \times 1.86 \times \left(\frac{u \times D^2}{L \times d_h}\right)^{\frac{1}{3}}} \qquad \text{Eq. (3.7)}$$

where L is the membrane length, d_h is the hydraulic diameter of the flow path and u is the cross-flow velocity.

The feed side ∂_F and draw side ∂_D boundary layer thicknesses can be evaluated by the following relation,

$$\boldsymbol{\partial = \frac{D}{K}} \qquad \text{Eq. (3.8)}$$

For Stage 2:

Assuming that the hydraulic pressure losses in the first stage of DSPRO process are negligible so they are often neglected. **(ΔP1=ΔP2)**

Hence to calculate the power density **w** developed across the membrane we can take the product of water flux and hydraulic pressure (Jonathan Maisonneuve et al., 2014),

$$\boldsymbol{w_2 = J_{w2} \times \Delta P} \qquad \text{Eq. (3.13)}$$

The total (net) power density for the dual stage PRO can be calculated by using the following equation,

$$\boldsymbol{w_{total} = (w_1 + w_2)} \qquad \text{Eq. (3.14)}$$

3.3 GANTT CHART FYP 1 & FYP 2

Below chart as show are the Gantt chart for Table FYP 1 and Table FYP 2 for better time management.

Table 3.4: Gantt chart of the timeline Final Year Project 1 from Week 1 (June) till Week 12 (August) 2020

		Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
	Week start	1/6/20	8/6/20	15/6/20	22/6/20	29/6/20	6/7/20	13/7/20	20/7/20	27/7/20	3/8/20	10/8/20	17/8/20
	Week End	5/6/20	12/6/20	19/6/20	26/6/20	3/7/20	10/7/20	17/7/20	24/7/20	31/7/20	7/8/20	14/8/20	21/8/20
Task/ Activity	Selection of FYP title												
	Collecting journals/articles												
	Identification of previous literature review												
	Submission of Progress Assesment 1 (SV)												
	Proposal defence preparation												
	Proposal defence presentation and submission												
	Project work												
	Submission of Interim Draft Report												
	Submission of Progress Assesment 2 (SV)												
	Submision of Interim Report												
	Meeting with FYP Supervisor												

Table 3.5: Gantt chart of the timeline Final Year Project 2 from Week 1 (January) till Week 12 (April) 2021

			Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
Task/ Activity	Project Development phase	Determine and evaluate the mathematical equations for PRO												
		Simulation of the PRO modules												
		Analysis the data												
	Submission phase	Progress report												
		Technical report												
		VIVA												

3.4 PROJECT MILESTONE

Below illustrated table is the overall project period which are the progress of each task.

Table 3.6: Project Milestone

Phase		Activity	Planned Duration	Actual Start	Percent Complete	Periods											
						1	2	3	4	5	6	7	8	9	10	11	12
FYP 1		Briefing on project	2	1	100%												
		Problem statement	3	1	100%												
		Literature review	9	3	100%												
		Identify type of membrane	12	3	100%												
		Conclude the methodology	12	5	100%												
		Project work	3	9	100%												
	FYP 2	Determine and evaluate the calculation	8	1	100%												
		Result	9	5	100%												
		Analysis data	11	5	100%												
		Report Submission	12	12	100%												

Task to be done

CHAPTER 4

RESULTS AND DISCUSSION

4.1 RESULTS

4.1.1 Flat Sheet (CTA) Membrane Stage-1

Using the experimental conditions and membrane geometry properties we calculated the values of the main parameters for the design of an osmotic power plant.

The concentration of draw solution was calculated in mol/L by dividing the salt concentration (mainly NaCl) in the draw solution with the molar mass of NaCl,

$$M = \frac{70g/L}{58.44\ g/mol} = 1.20\,\frac{mol}{L}$$

The experiment was carried out at a pressure of 2400 kPa (P_{in}), so to calculate the hydraulic pressure difference across the membrane outlet we first calculate the pressure losses at the feed and draw sides.

Reynolds number for the fresh feed is calculated as,

$$Re_F = \frac{0.000946 * 0.133 * 997}{0.892 * 1000} = 142.71$$

$$Re_D = \frac{0.000946 * 0.133 * 1021}{0.939 * 1000} = 138.83$$

Now to determine friction factors f_F and f_D,

$$f_F = 6.23 \times (142.71)^{-0.3} = 1.40654$$

$$f_D = 6.23 \times (138.83)^{-0.3} = 1.41822$$

Subsequently the pressure losses at the feed and draw sides can be accounted as,

$$P_{F,drop} = \int_0^{0.00075} \frac{1.4065 \times 997 \times 0.133^2}{2 \times 0.000964} dL = 9.68971$$

$$P_{D,drop} = \int_0^{0.00075} \frac{1.41822 \times 1021 \times 0.133^2}{2 \times 0.000964} dL = 10.0053$$

Hence the hydraulic pressure difference across the membrane outlet can be determined by Equation 3.4,

$$\Delta P = 2400000 - (9.6897 - 10.0053)$$

$$\Delta P = 2399999.68\ Pa$$

Now using Equation 3.7 to calculate the diffusion transfer coefficients for the feed and draw sides respectively,

$$K_F = 3 \times 1.86 \times \left(\frac{0.133 \times (1.49 \times 10^{-9})^2}{0.00075 \times 0.000964}\right)^{\frac{1}{3}} = 4.18 \times 10^{-4}$$

$$K_D = 3 \times 1.86 \times \left(\frac{0.133 \times (1.51 \times 10^{-9})^2}{0.00075 \times 0.000964}\right)^{\frac{1}{3}} = 4.15 \times 10^{-4}$$

Now using Equation 3.2 we will determine the osmotic pressure difference,

$$\Delta\pi = 2 \times 0.08205 \times 300.15 \times \frac{65}{58.44} = 54.78\ atm = 5550942\ Pa$$

Putting the value obtained from Equation 3.2 in Equation 3.1 to determine the water permeate flux,

$$J_{w1} = 5.91 \times 10^{-12}(5550942 - 2399999.68)$$

$J_{w1} = 1.6099 \times 10^{-5}\ m/s$

Similarly, Putting values in Equation 3.1.1 to calculate the salt flux,

$J_{s1} = 4.44 \times 10^{-8}(70 - 0)$

$J_{s1} = 2.89 \times 10^{-6}\ m/s$

Finally we will determine the power density by replacing values in Equation 3.3,

$w = 1.6099 \times 10^{-5} \times 2399999.68$

$$w_1 = 38.6365\ W/m^2$$

Table 1.1: Flat Sheet CTA Membrane Design Results for stage 1 process

Parameters	**Values**
Water Permeate Flux (J_{w1})	$1.6099 \times 10^{-5}\ m/s$
Power Density (w_1)	$38.6365\ W/m^2$
Salt Permeate Flux (J_{s1})	$2.89 \times 10^{-6}\ m/s$
Diffusion transfer coefficient (Feed) (K_F)	4.18E-04
Diffusion transfer coefficient (Draw) (K_D)	4.15E-04
Film thickness (feed) (∂_F)	3.61E-06
Film thickness (draw) (∂_D)	3.59E-06
Pressure loss on feed side (ΔP_F,drop)	9.68970 Pa
Pressure loss at draw side (ΔP_D,drop)	10.005348Pa
Hydraulic pressure difference (ΔP)	2399999.68 Pa

4.1.2 Flat Sheet (CTA) Membrane Stage-2

The concentration of draw solution was calculated in mol/L by dividing the salt concentration (mainly NaCl) in the draw solution with the molar mass of NaCl,

$$M = \frac{50 g/L}{58.44\ g/mol} = 0.86\frac{mol}{L}$$

Now using Equation 3.2 we will determine the osmotic pressure difference,

$$\Delta\pi_{\mathrm{D}} = 2 \times 0.08205 \times 300.15 \times \frac{35}{58.44} = 37.92\ atm = 3842959.9 Pa$$

$$\Delta\pi_{\mathrm{F}} = 426995.54\ Pa$$

$$\Delta\pi_{\mathrm{m}} = 3842959.9 - 426995.54 = 3415964.3\ Pa$$

Now, from Equation 3.1 based on the fundamental solution diffusion model of membrane permeation, we calculate J_w as,

$$J_w = 7.19 \times 10^{-13}(3415964.3\ - 2399999.68)$$

$$J_w = 7.30 \times 10^{-6}$$

Similarly, Putting values in Equation 3.1.1 to calculate the salt flux,

$$J_{s1} = 2.20 \times 10^{-8}(50 - 0)$$

$$J_{s1} = 9.90 \times 10^{-7}\ m/s$$

Assuming that hydraulic pressure losses in the first stage of DSPRO process are negligible. (ΔP1=ΔP2=2399999.68 Pa)

Therefore, we will determine the gross power density for stage-2 by replacing values in Equation 3.13,

$$w =\ 7.30 \times 10^{-6} \times 2399999.68$$

$w_2 = 17.5315\, W/m^2$

The total (net) power density for the dual stage PRO can be calculated by using Equation 3.14

$w_{total} = 38.6365 + 17.5315$

$w_{total} = 56.168\, W/m^2$

Table 4.2: Overall Membrane Design Results after the stage 1 process

Parameters	**Values**
Water Permeate Flux (J_{w2})	$\mathbf{7.30 \times 10^{-6}\, m/s}$
Power Density (w_2)	$\mathbf{17.5315\, W/m^2}$
Salt Permeate Flux (J_{s2})	$\mathbf{9.90 \times 10^{-7}\, m/s}$
Total power density (w_1+w_2)	**56.168 W/m^2**

4.2 DISCUSSION

4.2.1 Varying Hydraulic Pressure

In the above proposed DSPRO power plant, a rectangular flat sheet cellulose triacetate (CTA) membrane was being placed as the 1st stage and a similar configuration of flat sheet membrane was employed for the 2nd stage of the process and both the membranes were being tested subsequently for different experimental conditions. The draw solution entering the first and second stage of the process has a concentration of 70 g/L and 50 g/L of NaCl respectively. However various scenarios were considered during which $c_{Feed,\ bulk}$ was taken as 0, 5, 7.5 g/L of NaCl and water flux J_w was calculated at a range of ΔP equal to 0-5000kPa. Respective power densities for each condition was calculated and the conditions corresponding to maximum power density (peak of the plot) were taken as the optimum conditions to operate and design the proposed DSPRO power plant.

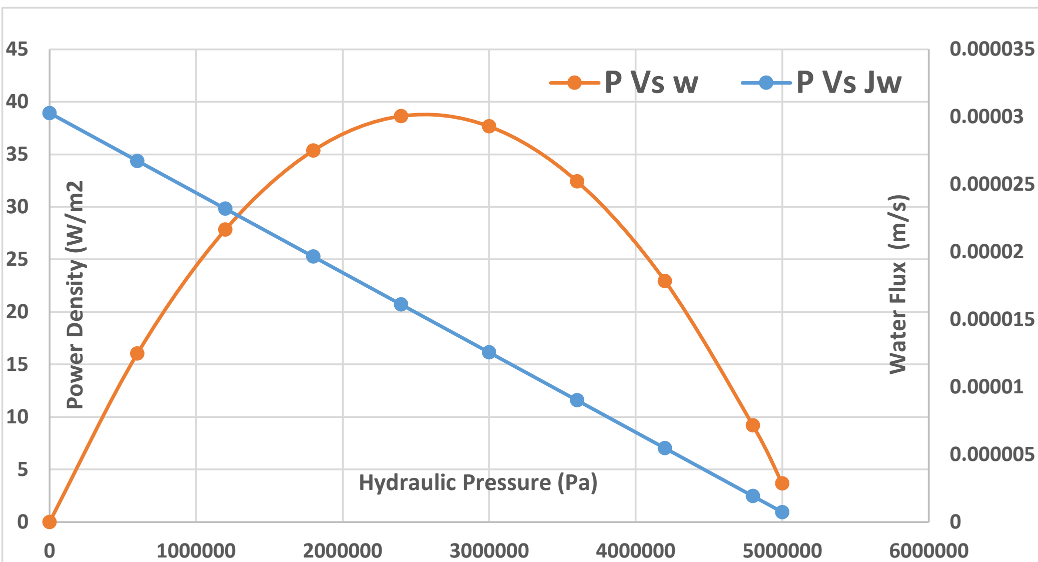

Figure 4.1:Model results for water flux (J_w) and power density (W) as a function of applied hydraulic pressure (ΔP) for Stage-1.

Theoretical water flux and power density curves as function of hydraulic pressure for stage 1 feed and draw concentrations of 5g/L and 70 g/L of NaCl are illustrated in Figure 4.1. Power density values are reported on the primary y-axis whereas the water flux values are reported on the secondary y-axis. In both cases, as hydraulic pressure increases, water flux decreases until approaches zero. Power density reaches a maximum (represented by the peak point on the curve) when the hydraulic pressure is approximately half of the hydraulic pressure of the point where the water flux approximately becomes zero. From Figure 4.2, in the case of the 70 g/L NaCl draw solution and nil g/L NaCl feed solution, the flux reversal point (where $J_w \sim 0$) occurs at 5000 kPa and the maximum in power density occurs at 2400 kPa with a value of 38.636 W/m^2 from the first stage.

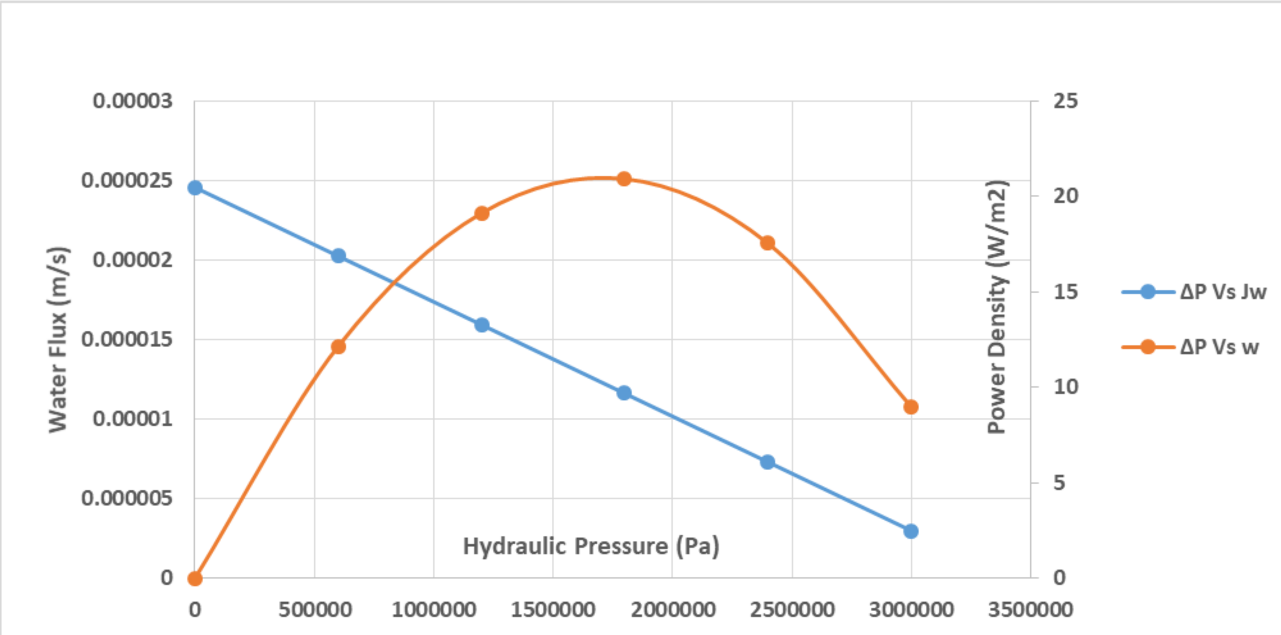

Figure 4.2: Model results for water flux (Jw) and power density (W) as a function of applied hydraulic pressure (ΔP) for Stage-2.

Similarly, for the second stage the diluted draw solution from the first stage with a concentration of 50 g/L NaCl enters the flat sheet membrane with 5 g/L NaCl of fresh feed. Assuming that hydraulic pressure losses in the first stage of DSPRO process are negligible. ($\Delta P1 = \Delta P2 = 2400$ kPa) so, the power density obtained from the Fig 3.4 is about 17.5315, which is relatively lower than that for the first stage and this is primarily due to the reduced salinity gradient between the two solutions resulting in a reduced osmotic pressure difference and effectively lower power density. From the model predictions in Figure 4.1 and Figure 4.2, it is estimated that the maximum power density can be between 12.14 and 20.91 W/m^2 for the second stage with a concentration of 50 g/L NaCl draw solution and between 32.4 and 38.6 W/m^2 for the first stage with a concentration 70 g/L NaCl draw solution. So from this study the threshold that has been set for successful development of osmotic power technology has been accomplished and the optimum set of conditions is being proposed to operate the DSPRO with maximum energy and power output.

4.2.2 Varying Feed Solution Concentration

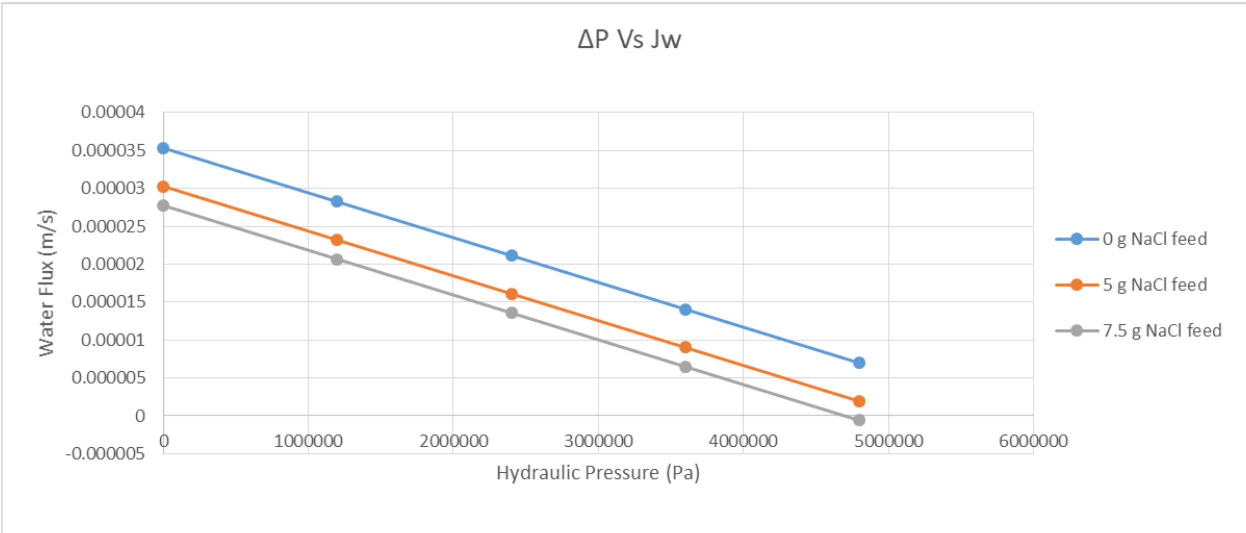

Figure 4.3: Model results for water flux (Jw) as a function of applied hydraulic pressure (P) for different feed solution concentrations.

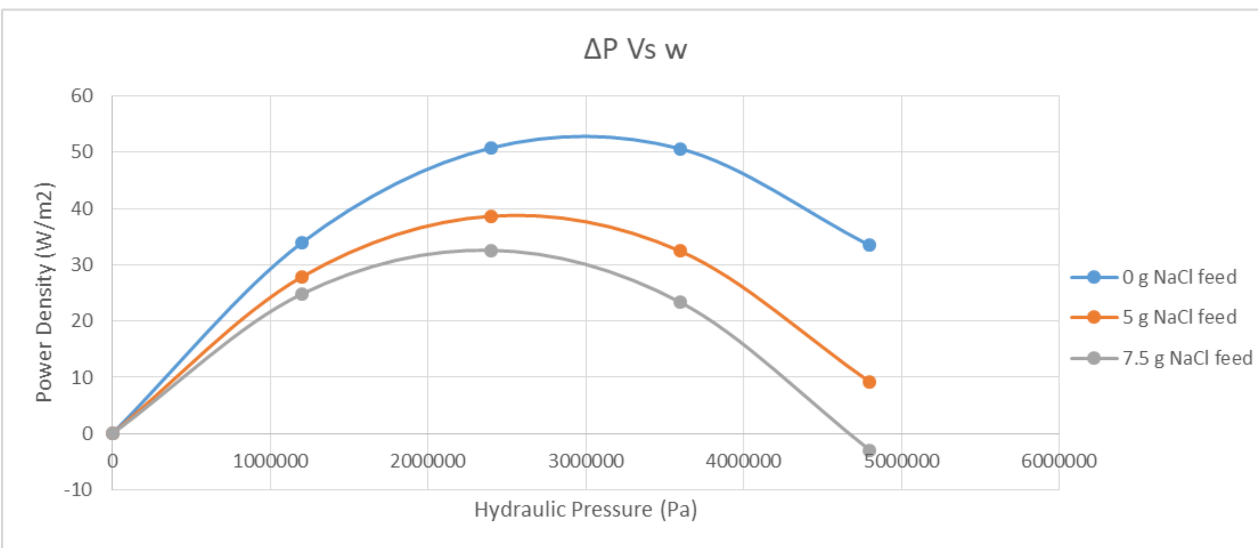

Figure 4.4: Model results for power density (W/m^2) as a function of applied hydraulic pressure (Pa) for different feed solution concentrations.

As the feed concentration increases, power density and water flux decrease because of the reduced mean osmotic pressure difference ($\Delta\pi_m$) between the two solution and also likely due to increased salt passage. From Figure 4.3, it can be seen that when the higher feed solution concentrations are used i.e. (0, 5 and 7.5 g/L NaCl), the water flux tends to decrease with the increasing concentration of the feed solution while the concentration of the draw solution is kept constant at 70 g/L NaCl in experimental conditions for stage-1. Similarly from Figure 4.4, a similar result could be concluded for the power density that as the feed concentration increases, the power densities tend to decrease. So choosing a feed solution with negligible NaCl concentration will yield more power owing to creation of a relatively lower mean osmotic pressure difference between the two solutions.

4.2.3 Varying Draw Solution Concentration

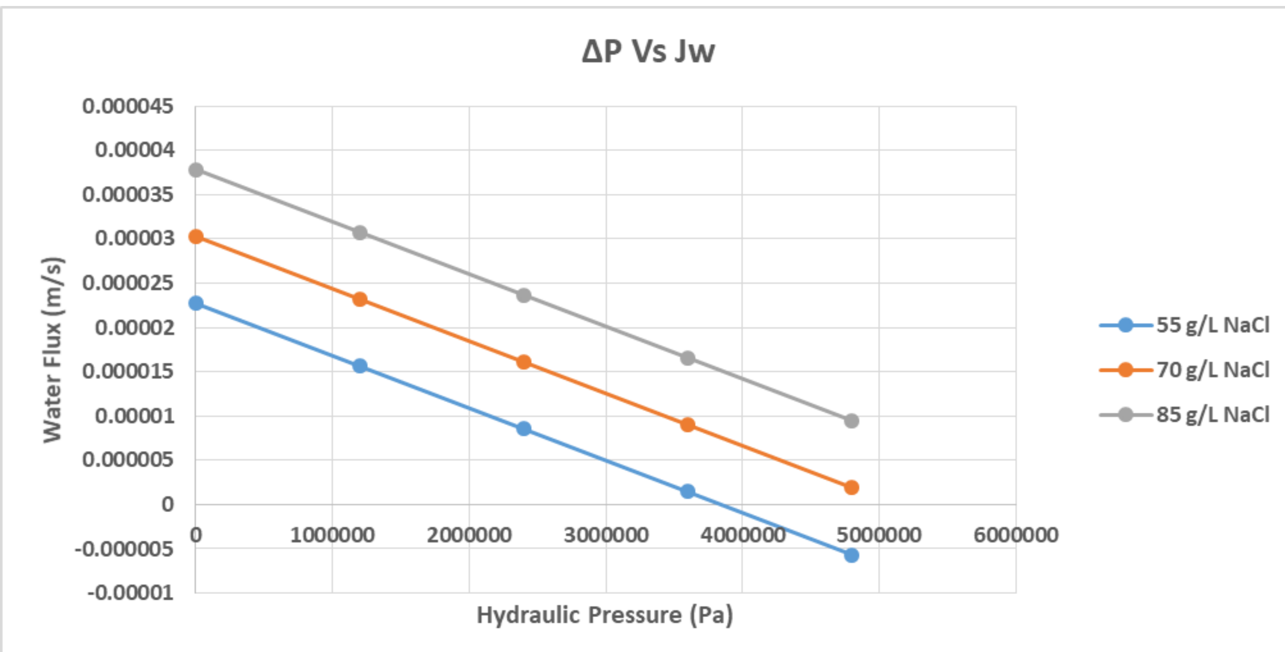

Figure 4.5: Model results for water flux (Jw) as a function of applied hydraulic pressure (P) for different draw solution concentrations.

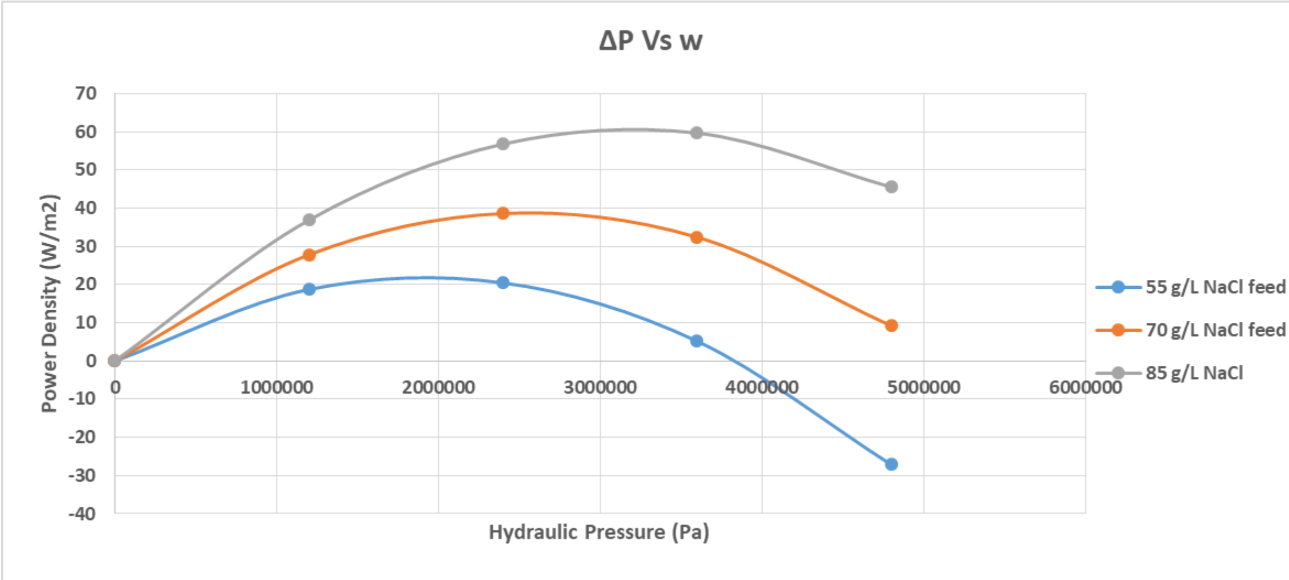

Figure 4.6: Model results for power density (W/m2) as a function of applied hydraulic pressure (Pa) for different draw solution concentrations.

As the draw solution concentration increases, power density and water flux also increase because of the increase in mean osmotic pressure difference ($\Delta\pi_m$) between the two solutions and also likely due to increased salt passage. From Figure 4.5, it can be seen that when the higher draw solution concentrations are used i.e. (55, 70 and 85 g/L NaCl), the water flux tends to increase with the increasing concentration of the draw solution while the concentration of the feed solution is kept constant at 5 g/L NaCl in experimental conditions for stage-1. Similarly from Figure 4.6, a similar result could be concluded for the power density that as the draw concentration increases, the power densities tend to show an increasing trend. So choosing a draw solution with higher salinity (NaCl concentration) will yield more power owing to creation of a relatively higher mean osmotic pressure difference between the two solutions.

4.2.4 Effect of Temperature on Water flux and Power Density

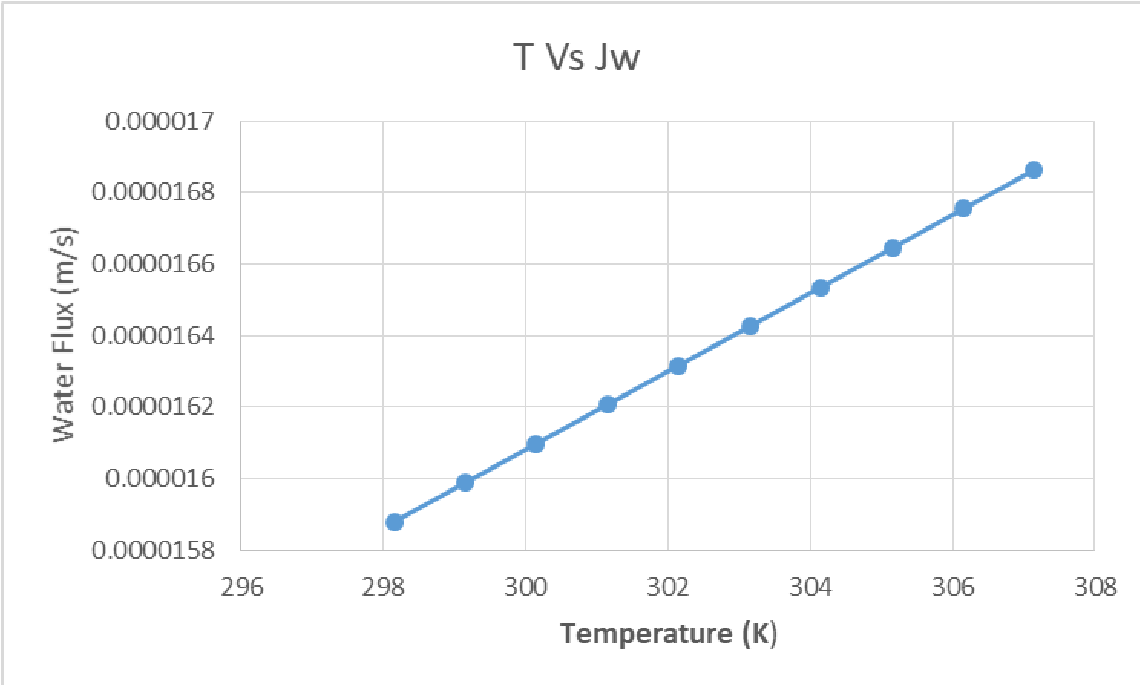

Figure 4.7: Model results for Water Flux (Jw) as a function of Temperature.

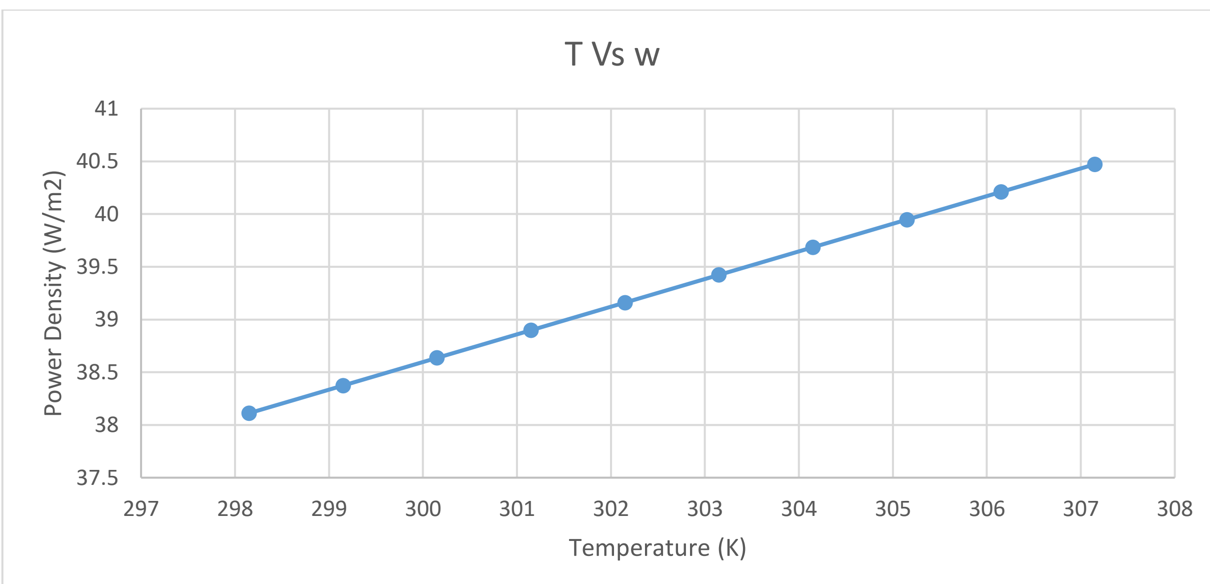

Figure 4.8: Model results for Power density (w) as a function of Temperature.

Operating temperature is a critical parameter that affects the performance of an osmotic plant. According to the Van't Hoff equation there is a direct proportional relation between osmotic pressure and temperature. In this modelling we keep the feed and draw solutions concentration constant of the 5g/L and 70g/L respectively. All values of water flux and power density are determined for the constant hydraulic pressure of 2400 kPa. Figure 4.8,illustrates that an increase in temperature improves the water flux and thereby reduce the operation time which is likely due to a decrease in the viscosity of water with increasing temperature. Similarly due to increasing temperature an increase in the osmotic pressure will occur which will result in relatively higher power densities as shown in Figure 4.9.

4.2.5 Varying water permeability parameter for membrane

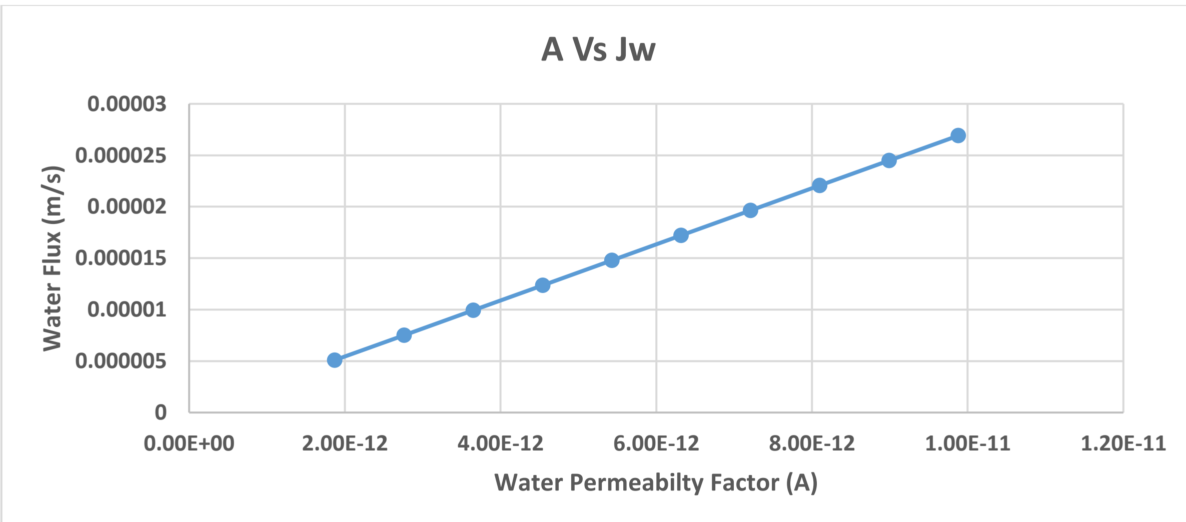

Figure 4.9: Model results for water flux (Jw) as a function of Water Permeability Factor of membrane.

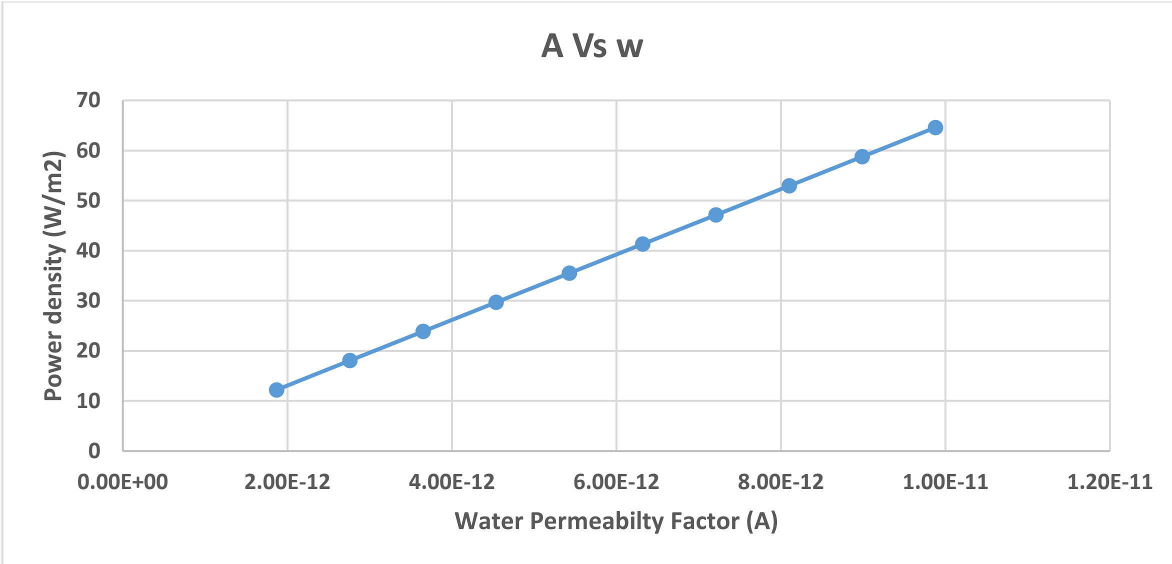

Figure 4.10: Model results for Power Density (w) as a function of Water Permeability Factor of membrane.

Figure 4.9 and Figure 4.10 illustrates that keeping the hydraulic pressure, temperature, feed and draw solution concentrations constant and using membranes with different water permeability factors (A) results in an increase in both the water flux and power density of the osmotic power plant.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

In conclusion, a number of alternatives are needed for a new energy sources. Nevertheless, osmotic power generation is an alternative energy sources in the future if the technology is further advance and the cost reduce. Although there is more effort should be carried out to explore few other factors in osmotic power generation, the evolution of technologies and membrane optimization been taking place endlessly to generate the PRO system to commercialization stage.

However, the objective of this project is to design and model a new pressure retarded osmosis with its operating parameters and to optimize osmotic power generation. There are several selected parameters has identified and analyzed. It has achieved by selecting particular factors which are investigated to perform effective osmotic power generation. All this investigation is done to verify productive PRO with the present technologies.

This project proposes a DSPRO system, using seawater and fresh water, as the draw and feed solutions. This proposal was evaluated in terms of the membrane power density obtained from performance data using a unique membrane configuration composed of a flat sheet membrane followed by a second stage flat sheet membrane module.

In this investigation, the DSPRO model was developed to predict water flux and power density under specific experimental conditions. For the 1st Stage of DSPRO system, we employed a flat sheet membrane CTA configuration and by plotting the experimental data we found the optimum operating conditions, so at 2400 kPa hydraulic pressure on the draw solution side, the water permeate flux came out to be $\mathbf{1.6099 \times 10^{-5}}$ m/s and gross power density for stage 1 achieved was up to **38.6365 W/m^2** for the 70 g/L NaCl draw solution.

The diluted draw solution with a concentration of 50 g/L NaCl was introduced to the 2nd Stage and assumed that since the hydraulic pressure losses were minimal so, ΔP1=ΔP2=2399999.68 Pa across the membrane. The water permeate flux came out to be $\mathbf{7.30 \times 10^{-6}}$**m/s** and gross power density for stage-2 achieved was up to **17.5315 W/m^2**. Finally, both the gross power densities were combined and the net or total power density achieved for the proposed DSPRO system was up to **56.168 W/m^2.**

5.2 RECOMMENDATION

Many studies have revealed that the power output from a single stage commercially available PRO membrane modules is insufficient to realize an economically viable PRO energy generation system. Therefore, using multistage PRO systems and increasing membrane modules up to a limited extent can dramatically improve the power density of the system for the effectively the same membrane area. Different membrane configuration with varying parameters i.e., water permeability (A) and salt permeability (B) to can also significantly alter the efficiency of the plant and can be manipulated to achieve maximum power density. The feed and draw solutions with an appreciable difference in their concentrations will be preferred as they will provide a higher salinity gradient and resultantly a higher osmotic pressure difference between the two solutions aiming to increase the power density of the process.

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