Theoretical Assessment of Dual Stage Pressure Retard Osmosis (PRO) Process for Power Production Utilizing Seawater and Fresh Water

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Abstract

Pressure Retarded Osmosis (PRO), as a type of renewable energy resource, has been suggested and investigated for power generating from salinity gradient resource. Conversely to other renewable energy resources, such as solar and wind energy, PRO can be worked along 24- hours, where, it is not affected by solar radiation or wind and it can be established on a small area. It has a less scale-up problem and it can be used as a pre-treatment of the RO rejection. Nevertheless, PRO process is not commercialized yet.

In this study a dual stage PRO processes is proposed for power generation utilizing osmotic energy. Seawater and fresh water were used as the draw solution and the feed respectively. Different operational parameters, such as membrane area, feed flow rate and draw solution flow rate were tested. The values of these parameters were tabulated as three different cases throughout the calculations. The results showed that the flux of water decreases with increasing the applied hydraulic pressure on the draw solution side. Both the net power production and the power density have optimal values at applied hydraulic pressure equal nearly 20 bar.

Introduction

Pressure retarded osmosis (PRO) power generation fromthe osmoticpressure gradient across a semipermeable membrane has received anextraordinary attention as an up-and-coming technology to reduce fossil fuel use for power generation [1–2]. In principle, the high concentration solution (draw solution) is pressurized before it goes to the PRO module for water extraction from the low-concentration feed solution. The chemical potential converts to a hydraulic pressure as fresh water permeate across the membrane [3]. Power generation takes place as the draw solution is depressurized in the hydroturbinesystem. One of the key factors for a successful PRO process is the high membrane permeabilitywhich requires a special manufacturing design that reduces the effect of concentration polarization at the membraneHypersaline solution is a wastewater generated from industrialactivities such as oil and gas industries. It is characterized by the highconcentrationof total Dissolved Solids (TDS) which is normally morethan seawater concentration of 35 g/L. Such wastewater is difficult totreat by the conventionalwater treatment technologies such as ReverseOsmosis (RO) and Bioreactors [6–7].

Energy and water sustainability is an important issue for the existenceof modern life in developed and semi-developed countries[8–9]. Unfortunately, the resources for water and energy supply becomescarce every day due to the population increase, environmental pollutionand the rapid industrial growth. In fact, the growing concerns about thedepletion of these resources in the near future have encouragedscientists to find new resources for energy and water supply. Forwardosmosis (FO) and Pressure Retarded Osmosis (PRO) processes areemerging technologies which have the potential for fresh water and energy supply at competitive costs [10–11]. These technologies are based on the concept of osmotic pressure gradient applications across a semipermeablemembranefor power and freshwater supply. A proper salinitygradient resource, therefore, is required for the operation of FO andPRO processes. Several studies proposed that seawater and wastewatereffluent are the draw and feed solutions of the PRO process [10,11,12].

which can be further processed either for desalination or powergeneration. For seawater desalination, a suitable membrane or thermalprocess is required for fresh water extraction and draw solution regeneration[13-14-15-16]. If the FO process is designed only for power generation,the draw solution will be pressurized before entering the PROmodule. In the PRO module, the chemical potential is transferred to ahydraulic pressure as fresh water permeates across the membrane[17-18]. The power generation takes place in the turbine system whenthe pressurized draw solution passes through. In arid and semi-aridareas, the diluted draw solution can be further treated by an ROmembrane for fresh water supply instead of discharge to the seawater[13-19-20-21-22]. In fact, recent PRO designs suggested combining the PROmodulewith an ROmembrane system in order to reduce the cost of seawaterdesalination [21-23]. Combining PRO with RO reduces the cost ofRO feed pretreatment as well [21]. Several PRO-RO, RO-PRO and FO-ROhybrid designs have been investigated in the literature [19-21].These systems are not only able to reduce the cost of seawater desalinationbut also able to generate a useful power by the PRO process. Achilliet al. proposed a hybrid RO-PRO system for seawater desalination andpower generation [24].

2. The PRO process

The concept of osmotic power or salinity gradient was introducedfirst in 1954 by R.E. Pattle[24]. However, the concept has been furtherdeveloped by Sidney Loeb who proposed using salinity gradient forpower generation [25-26]. In general, the PRO process has been tremendouslyevolved since 1973 because of the rapid development in membranetechnologies. At the beginning, the major challenge towards thedevelopment of PRO technology was to find a suitable membranewhich has moderate mechanical stability, high water permeability andhigh salt rejection rate [25-26-27-28]. The new generation of FO membraneshave overcome this proble,m through reducing the thickness of the membrane support layer which became thinner than conventionalRO membrane [29–30]. Therefore, Forward Osmosis (FO) membranecan not tolerate high feed pressures. Yet, osmotic power is still facingseveral challenges to be addressed before it can be fully commercializedsuch as membrane type, membrane fouling, optimization of operatingparameters, and type of draw solution and regeneration of draw solution.These issues will be discussed in the following sections in light ofthe recent development in the PRO process technology.

3. PRO process description

Osmotic energy is the energy released when freshwatermixes withsalt water [24-31]. The major components of the PRO power plant arei) PRO membrane module and ii) hydroturbine system to convert the hydraulic energy to electricity.

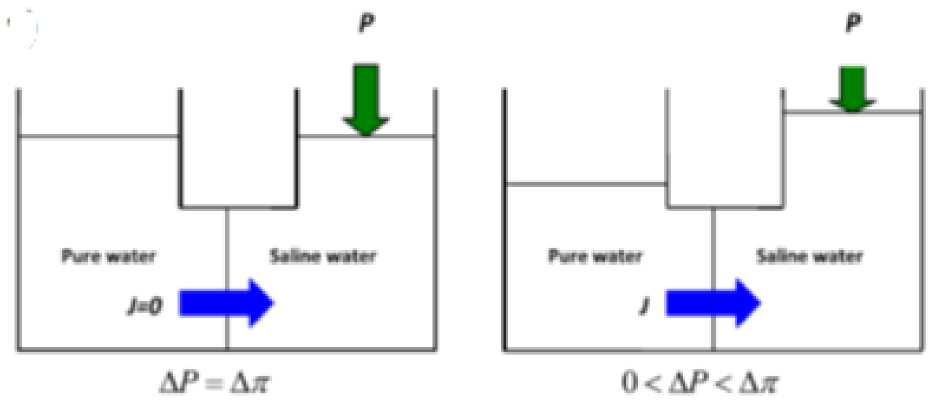


Fig.1 Pressure retarded osmosis

The structure of PROmembrane is somehowsimilarto that of the ROmembrane but the porous support layer inthe PRO membrane is thinner than that in the conventional RO membrane.Additionally, the PRO membrane should enjoy good mechanicalstrength to withstand the applied hydraulic pressure on the draw solutionside of themembrane.

In the PRO process, draw solution is pressurizedup to 30 bar, depending on the osmotic pressure of draw solution,and sent to a special semipermeable membrane while low osmoticpressure solution is circulated on the opposite side of the membrane(Fig. 1). Fresh water permeates across the membrane and dilutes thehigh-concentration draw solution. After leaving the membrane, thepressurized diluted draw solution goes to a turbine system to convertthe hydraulic energy into electricity. Finally, the diluted draw solutionis either discharged to the sea or treated by membrane or thermal processesfor regeneration and reuse [25–32]. Seawater is a good draw solutioncandidate because of its relatively high osmotic pressure, free ofcost (excluding pumping, pretreatment, etc. cost), and availability [33,34-35-36].

It has been estimated that a maximum energy of 0.8 kWhcan be generated when 1 m3 of river water flows into seawater [37].Of course this is depending on the salinity level of the seawater. However,

4.mathematics description

in the PRO process net energy after pre-treatment and extrapumping is about 0.2 kWh/m^3. The general equation to estimate thePRO membrane water flux, Jw (L/m^2H), is:

$Jw = Aw(\Delta\pi - \Delta P)$……………………………..(1)

Where, A_w is the coefficient of meاكتبالمعادلةهنا.mbrane permeability ($L/m^2h.bar$), $\Delta P$is the differential feed pressure across themembrane (bar) and $\Delta\pi$ is thedifferential osmotic pressure across the membrane (bar). In the PROprocess, power density, W (W/m^2), is the power per unit membranearea and it is equal to the product of the membrane water flux multipliedby the differential hydraulic pressure across the membraneaccording to the following equation:

$W = J_w \Delta P$……………………………………….(2)

Substituting 1 in 2 to give the following equation:

$W= Aw(\Delta\pi-\Delta P)\ \Delta P$…………………………….(3)

Lee et al (2006). investigated the impact of ΔP on W and J_w as shown in Fig. 1[37].

It has been found that the power density reaches a maximum theoreticalvalue, W_{max}, when the hydraulic pressure is equal to the halfvalue of the osmotic pressure gradient ($\Delta P = \Delta\Pi/2$) across the PROmembrane. Eq. (3) can be rearranged to calculate W_{max}:

$W_{max}= A_w\ \Delta\pi^2/4$……………………………..(4)

The total power generation, Pwt (kW/d), were calculatedfor both systems, i.e. the old and new, using the following
equations:

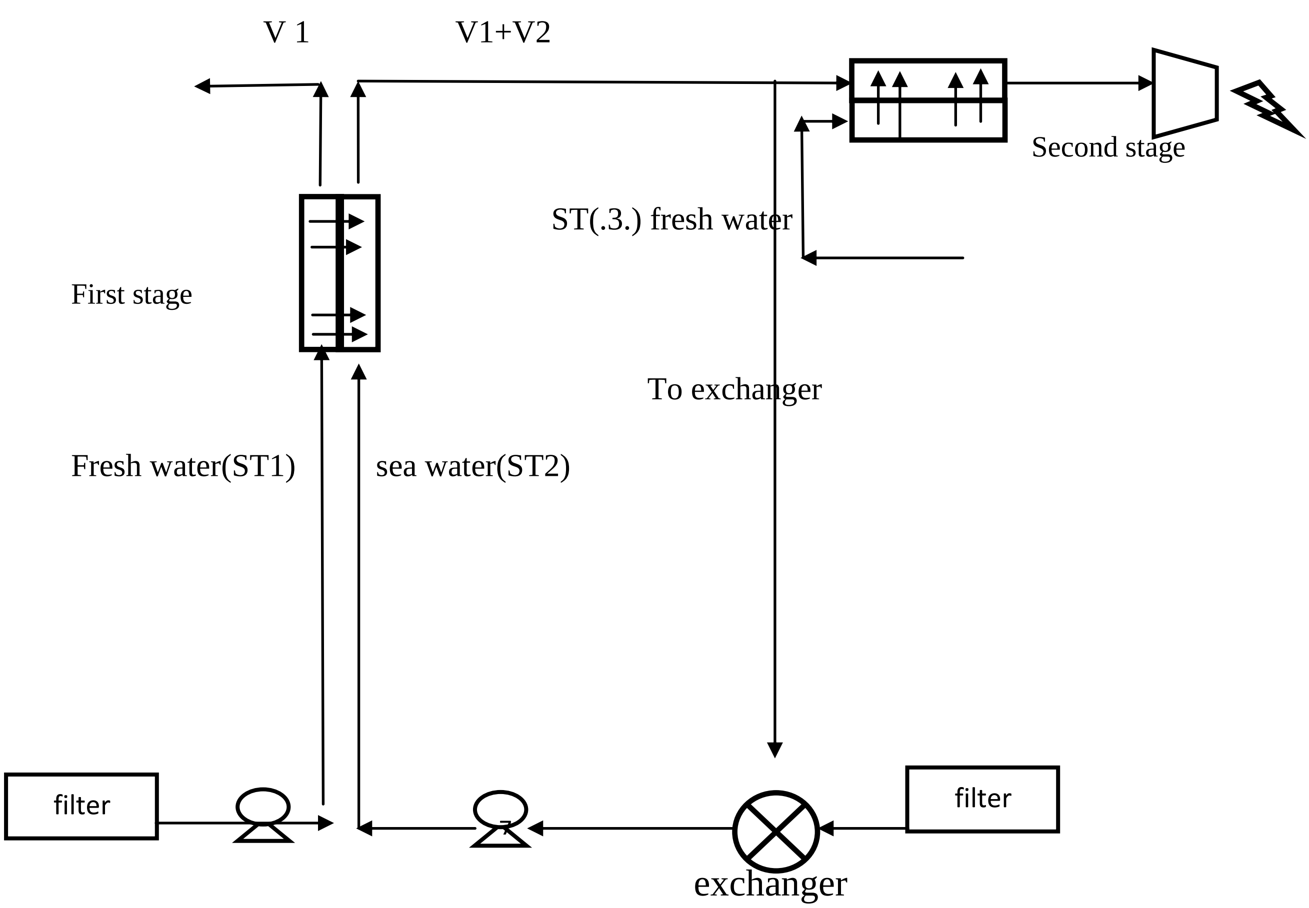
$W = \Delta P\ \ J_W$……………………………….(7)

The power output,
Pwt (W), in dual stage PRO process is estimated from the following
equation:

$P_{wt}= \Delta P\ (\ Q_{p1}+Q_{p2})$……………………..(8)

Qp1 and Qp2 are the first and second stage rate permeate flow respectively(m^3/h). Power density is the power generated per unit area ofmembrane and it is a key parameter to estimate the efficiency of thePOR process. Increasing membrane flux has proven to have positiveimpact on the process efficiency.

The operating mechanism of dual stage PRO process is illustrated inFig. 2. Pretreated seawater is pressurized and sent to the PROmodule forfresh water extraction from the low concentration feed solution. Thepressurized seawater flow is divided into two flows after leaving thePRO module. The first flow, QR, is equal to the flow rate of draw solutionfeed, Qds-in, and returns to a pressure exchanger (PX) to pressurize theseawater feed. The second flow, V1, which is equal to the permeateflow rate goes to the second PRO module for further treatment.



Figure(2) schematic diagram of the dual stage PRO system

Although it has lower concentration than raw seawater, the osmoticpressure of pressurized seawater to the second stage of PRO process isstill considerably higher than that of the wastewater effluent feed(Fig. 2). In the second stage of the PRO process, freshwater permeatesacross the membrane in the direction of

draw solution resultingin increasing the volume of pressurized seawater by an amountequivalent to the permeate flow rate, V2. The generated flow rate,
V1+V2, is employed for power generation through depressurizationthe seawater in a hydroturbine system. It is worth mentioning herethat the second stage of PRO process does not require extra energyfor pumping the draw solution into the membrane module. However,the water flux in the second stage of PRO process is lower than that inthe first stage of the PRO process because of the lower osmotic energyof the draw solution. Ignoring pressure losses due to friction forces,it is assumed here that the hydraulic pressures of seawater in the
first and second stage of PRO process are equal. Comparing with the conventional PRO, the dual stage PRO processgenerates more power for the same flow rate of drawsolution but it requiresmore membrane area than single stage PRO process. Mathematically,this can be described by comparing Eqs. (1) and (2). The netpower generation in dual stage PRO process is higher than that in conventionalPRO process by an amount equal to ΔP*V2.Practically, high foulants concentration feed solution is introduced inthe second stage of PRO process while the lowfoulants and/or high TDSsolution is introduced in the first stage of PRO process. The advantages of this arrangement are the following: firstly the lower water flux inthe second stage of PRO process alleviates the membrane fouling propensitycaused by the wastewater feed and secondly the performanceof PRO process, represented by the permeate flow, is higher when thehigh concentration feed solution is introduced in the first stage of PROprocess. Technically, the internal concentration polarization is more
serious than the external concentration polarization and causes asharp decrease in the permeate flow rate [15]. However, the decreasein permeate flow rate becomes more significant when the brackishwater is introduced in the second stage of PRO process due to thelower concentration of draw solution in the second stage than in thefirst stage. Unfortunately, the internal concentrative concentrationpolarization cannot be minimized by increasing the feed flow rate.

Consequently, introducing brackish water in the second stage of PROprocess compromises themembrane flow rate appreciably and thereforereducing the power generation as per Eq. (2). Pre-developed software was employed throughout the study to estimate the performance ofPRO process in both stages 1 and 2.

5.Result and discussion

Figure 3shows the relationship between the flux of water with the hydraulic pressure for different operational conditions given in table (1).

Table (1): the input of the parameter for duel PRO system

	case. 1.	case. 2.	case. 3.
Membrane area(m^2)	**35000**	**70000**	**100000**
Flow rate of the feed (first stage) (Kg/h)	**500**	**1000**	**2000**
Flow rate of the draw solution (first stage)(Kg/h)	**50000**	**100000**	**200000**
Flow rate of the feed solution(second stage) (Kg/h)	**5000**	**10000**	**20000**

It is clear that the increase in the hydraulic pressure leads to a decrease in the flux of water that passage through the membrane.This could be due to the decrease in the net pressure driving force over the membrane.

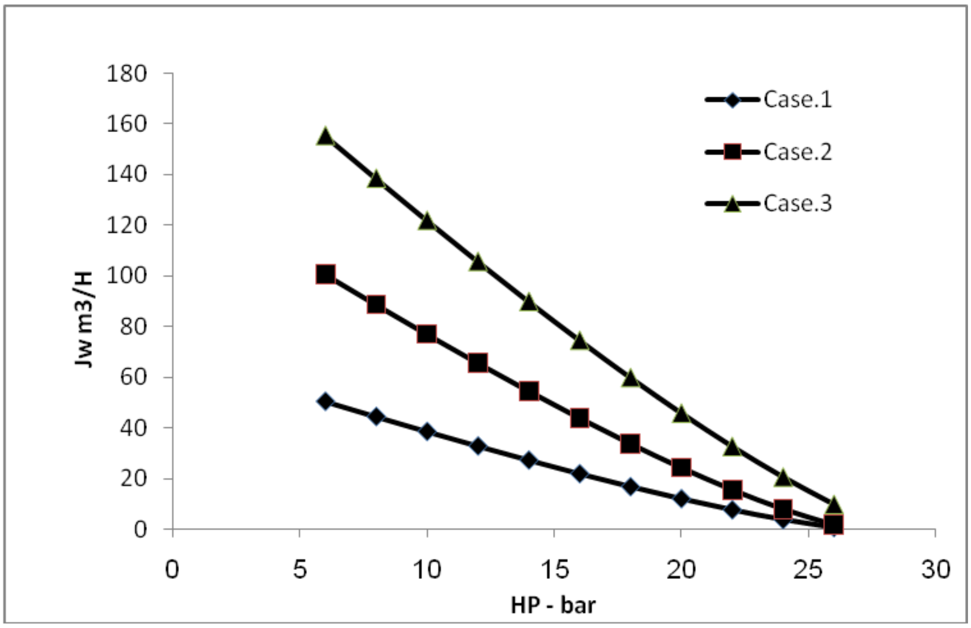


Figure 3. Water flux versus applied hydraulic pressure

However, the water Flux is calculated using equation (1) above, which clearly tells as that when $\Delta\pi$ less than ΔP,a reverse osmosis process is normally occurred. Consistently, when $\Delta\pi = \Delta P$, means no water passes through membrane, while only when $\Delta\pi$ greater than ΔP, useful forward osmosis is achieved. According to the calculations, the critic hydraulic pressure was found to be equal to 26 bar.

Figure 4shows the relationship between the net power production with hydraulic pressure for the three operational conditions or cases given in table (1).As shown by the figure, higher power can be produced by increasing the applied hydraulic pressure., The third case of the operation conditions exhibits the higher power production throughout the process.It Is obvious that for all three cases under study, the power produced increases with hydraulic pressure until it reaches the optimal value corresponding to the applied hydraulic pressure nearly 20 bar. Thereafter, the power produced decreases with the hydraulic pressure. The maximum power production for the three cases was 121.22 kW, 69.08 kW and 34.54 kW for case three, two and three respectively this cases will treatment with constant membrane area and draw solution and feed solution.

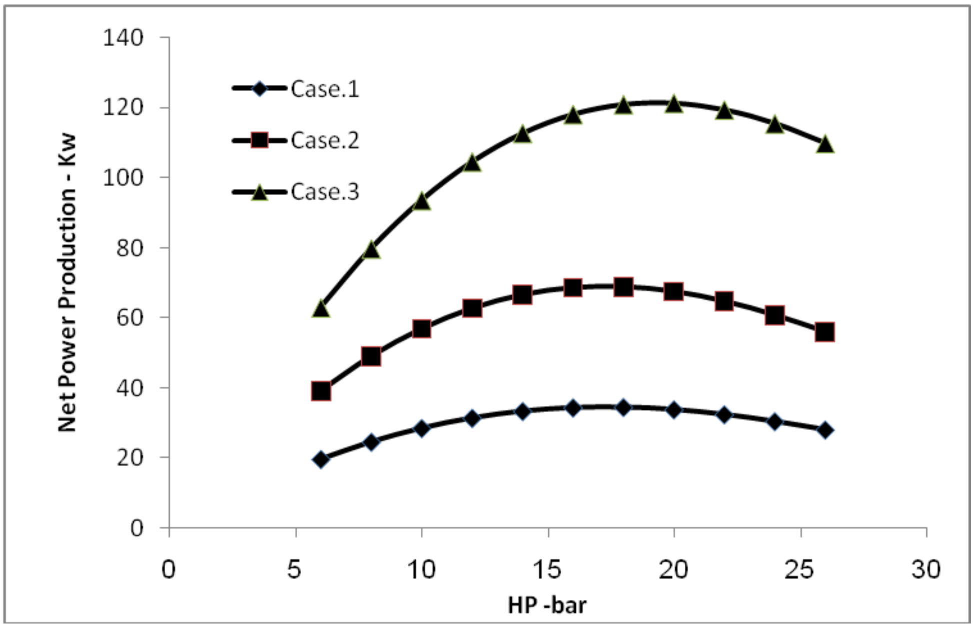


Figure 4. net power production versus applied hydraulic pressure

In figure 5the variation of power density with applied hydraulic pressure for the three operational conditions is presented. Apparently, the power density increases with increasing the applied hydraulic pressure in similar minor to that shown by Fig. 3. Hence, the behavior of the power density exhibits an optimum values at a given value of the applied hydraulic pressure. Interestingly, this value of the applied hydraulic pressure was nearly the same as that already found for the case of the power production (nearly 20 bar). The optimum values for the power density was 4.873, 2.793 and 1.396 W/m2, for the cases under study three, two and one respectively. This indicates that the operational condition of case three (see table 1) represents the best one which can give maximum power production as well as power density.

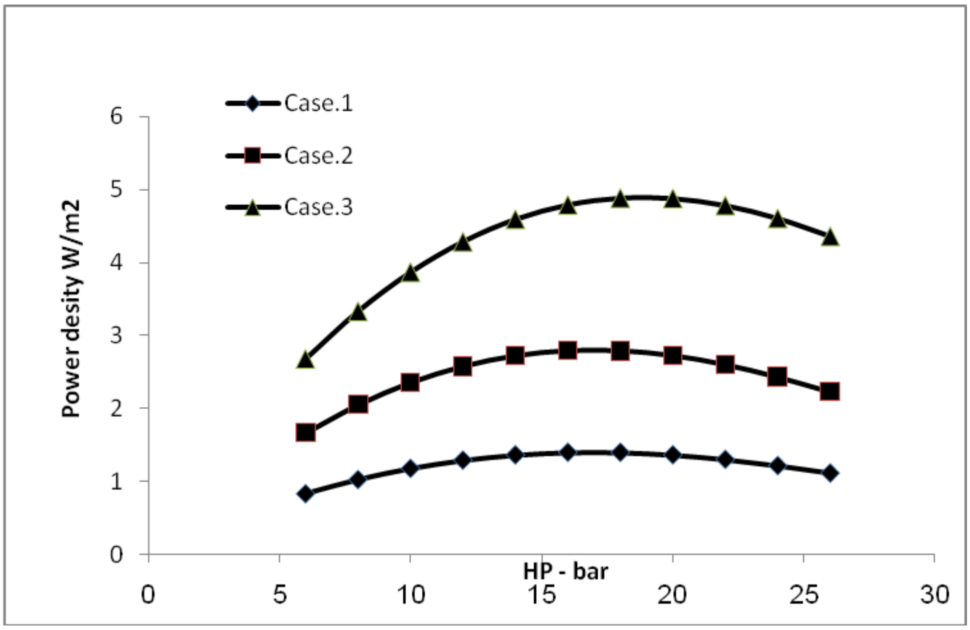


Figure 5. power density versus applied hydraulic pressure

6.Conclusions:

Theoretical assessment of a dual stage PRO process using for power production was presented. Different operational parameters were tested. However, the results have been led to that the net power production is increased with applied hydraulic pressure until an optimal value depending on the osmotic pressure of draw solution. In the present study, the optimal hydraulic pressure was about 20 bar. Consistently, the membrane power density was had the same behavior of the net power production. Finally, the present design offers a high efficiency with low fouling problems.

الخلاصه

ان الضغط التناضحي الاوزموزي يعتبر واحد من مصادر الطاقهالمتجدده ،من خلال أختلافالكثافه للماء وجدنا ان هذا مصدر لتوليد الطاقه بتقنية الضغط التناضحي بالاضافه الى هذا ان هذه الطريقهبأنتاجالطاقه ليس كطاقة الرياح او الشمس فهي ممكن العمل بها على طول اليوم (٢٤) ساعه،وهي كذلك ليس كطاقة الرياح او الشمس التي تحتاج لمساحة كبيره بالمقارنهمعها،بالاضافه الى هذا فأن المشاكل المصاحبهلأنتاج هكذا طاقه أقل من نظيراتها ولو هي لحد الان لاتعتبرناجحهتجاريا.في هذه الدراسه استخدمنا وحدتين للضغط التناضحي لانتاجالطاقه .تم استخدام ماء البحر والنهر كمصدر ،مع أستخدامبارمتراتمختلفه كمساحة الممبير والمصدر للمياه كتغذيه المتمثل بماء النهر والبحر مع تغيير في قيم البارمتراتالثلاثه وجد في هذا العمل أن كمية المياه المتدفقه تقل بزيادة الضغط الهيدروليكي المطبق على مصدر المياه المتمثل بمياه البحر .ووجد ان كلا من كمية الطاقه او القدرة المنتجه وكذلك كثافة الطاقه انها كانت في افضل قيمه عندما كان الضغط الهيدروليكي يساوي تقريبا ٢٠ بار

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