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Application of salinity gradient power for brines disposal and energy utilisation

M. Ahmad*, P. Williams

Centre for Complex Fluids Processing, School of Engineering Swansea University, Swansea, United Kingdom
Tel. +44 7798657721; Fax +44 1792 295676; email: ahmedddus@hotmail.com, paul.melvyn.williams@swansea.ac.uk

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ABSTRACT

Disposal of high saline brines is a common and important problem in many industrial plants. These waste streams may be generated in large volumes in many different industries. It is well known that these concentrated brines cannot be desalted by using the conventional desalination technologies due to two crucial factors which are; cost and reliability. Moreover, these factors have limited the scope of choice of other desalination processes for such applications. Hence this paper is aimed at providing an ideal disposal method that is economically and technically capable of producing energy by mixing and then disposing of high saline brines into a large body of water, with least harm to the environment. In this paper, various concepts in the utilisation of salinity gradient power are discussed to highlight what kind of methods are being proposed around the world for the energy exploitation, and also several novel ideas were addressed in this study to present the possibilities of implementing the osmotic power plants as a dual purpose plant (power plus disposal). In addition, the paper shows the results of the mathematical calculations for the amount of energy that can be generated by mixing high saline brines (with a TDS of 100,000 ppm up to 250,000 ppm) and different sources of water. These calculations have been performed for mixing of high saline brines with: river water (with an average TDS of 300 ppm), Normal Ocean seawater (35,000 ppm), Arabian Gulf seawater (46,000 ppm) and municipal wastewater (10,000 ppm). When mixing 1 m^3 of concentrated brine (100,000 ppm) with 1 m^3 of river water at 25°C, 1.6 kWh of energy can be generated, whilst for 1 m^3 of concentrated brine (250,000 ppm) with 1 m^3 of river water, 4.03 kWh is generated. This amount of energy becomes greater by increasing the volume ratio. For Normal Ocean seawater the results show that the maximum and minimum energies available (at a volume ratio of 1) are 2.15 and 0.38 kWh, respectively, for the mixing of seawater with concentrated brines of 250,000 and 100,000 ppm. While the maximum and minimum energy available decreased to 1.82 and 0.24 kWh, respectively if the concentrated brines of 250,000 and 100,000 ppm are mixed with the Arabian Gulf seawater. The amount of energy available when mixing the concentrated brines and municipal wastewater have also been determined, and the results show that the maximum and minimum amount of energy available (at a volume ratio of 1) are 3.24 and 1.01 kWh, respectively at brine concentrations of 250,000 and 100,000 ppm. Hence the advantages and also the theoretical results proved that the osmotic power plant might be competitive with other brine disposal processes, because the outcome would render several benefits including; utilisation of alternative energy, a significant amount of energy available can be generated, safe disposal, and the energy produced is completely renewable and sustainable, clean, and green since it does not produce CO_2 or other significant effluents that may interfere with the natural climate.

Keywords: High saline brine; Salinity gradient power; Reversed electrodialysis (RED); Pressure retarded osmosis (PRO); Brine disposal process

* Corresponding author.

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1. Introduction

Disposal of high saline brines (which in some industrial processes can have a TDS in the region of 100,000–250,000 ppm) is a common and important problem in many industrial plants. These waste streams may be generated in large volumes in many different industries such as the food processing, electrical power generation, water desalination and oil/gas industries. It is well known that the high saline brines cannot be desalted by using the conventional desalination processes due to two crucial factors which are; cost and reliability. Moreover, these factors have limited the scope of choice of other desalination processes for such applications.

At present, the utilisation of non-conventional energy sources is one of the major challenges of applied research. This is particularly relevant as the price of conventional energy sources, which are produced by burning fossil fuels, has reached a high level. This means that alternative energy sources are becoming competitive. One of these alternatives is the salinity gradient method, which produces energy when electrolyte solutions of different concentrations are mixed. Furthermore, this method is completely renewable, sustainable, and has the highest energy concentration of all marine renewable energy sources [1], as demonstrated in Table 1.

In principle, this method is clean and green because it does not consume a fuel or produce CO_2 emissions. Despite its potential and advantages, salinity gradient energy is an often-overlooked source of marine renewable energy.

The successful application and commercialisation of osmotic power plants is dependent mainly on the existence of two solutions having a high flux, and a high level in concentration difference. Hence, industries which are producing large volumes of high saline brines are attractive areas for osmotic power plants, because with a greater concentration difference between two streams, energy production will increase drastically.

Therefore, this paper presents an application of a dual purpose plant (power plus disposal) using an osmotic power plant. This system is capable of producing energy prior to disposal of the brine. The application of this disposal method depends on the possibility for dumping the high saline brines into a large saline water body. If this is environmentally and economically feasible, then the incorporation of an osmotic power plant may allow disposal of the brines and as well as harvesting of a certain amount of electrical energy by utilising salinity gradient power. This also lessens the environmental hazards, as although the total amount of solutes dumped into the reservoir remains unchanged it will reach the water body at a lower level of salinity thus reducing the creation of very steep salinity gradients and excessive osmotic pressure. However, it is important to mention that its application and viability depends on several factors including: site specific, environmental impact, chemical compositions, volume, and concentration of diluted and concentrated solutions [1,2].

Table 1
Marine renewable resources [1]

Resource	Power (TW)	Energy density (m)
Ocean currents	0.05	0.05
Ocean waves	2.7	1.5
Tides	0.03	10
Thermal gradient	2	210
Salinity gradient	2.6	240

2. The principle of osmotic power

The principle behind the osmotic power is the exploitation of the entropy of mixing two solutions with different salt gradients. When incorporating a semi-permeable membrane between two compartments containing diluted and concentrated solutions respectively, a net flow of diluted solution towards the concentrated solution side will be observed because of the osmosis phenomenon. If the compartment volume on the concentrated solution side is fixed, then the pressure will increase towards a theoretical maximum of 26 bar for seawater applications. This pressure is equivalent to a 270 m high water column [3].

3. Osmotic power technologies

Various concepts on the exploitation of salinity gradient power were proposed over more than twenty years ago. Pressure retarded osmosis (PRO) and reverse electrodialysis (RED) are the most frequently studied membrane-based processes for energy conversion of salinity-gradient energy. These concepts and two more techniques, vapour compression and a hydrocratic generator, are presented briefly in this paper. Readers can discover more details on these technologies through the listed references [1–15].

3.1. Reversed electrodialysis (RED)

The first proposal which intended to utilise a salinity gradient as a source of energy came in 1950s in a form which resembles very much the reverse electrodialysis process [4]. In this process, as the term implies, the electrodialysis process is reversed. When a concentrated solution flows through alternating cells and diluted solution flows through the others, a voltage is generated across each ion-exchange membrane.

Fig. 1 illustrates the main components of a reverse electrodialysis (RED) stack. In the stack, many cation-

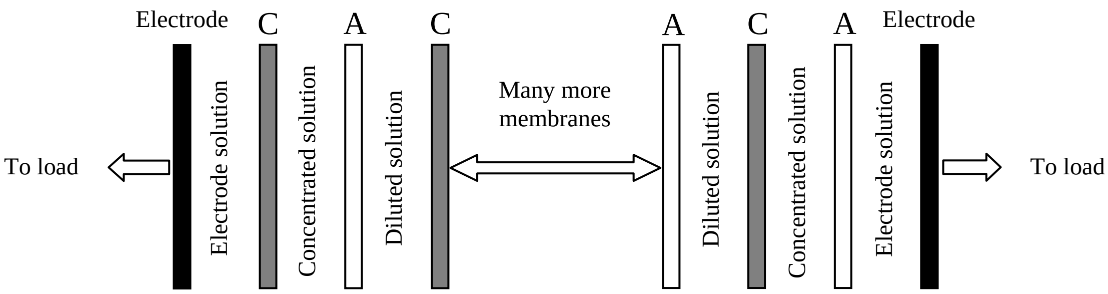

Fig. 1. Schematic diagram of a reverse electrodialysis stack.

exchange (C) and anion-exchange (A) membranes are arrayed alternately between a pair of electrodes, with an anion-exchange membrane followed by a cation-exchange membrane. The concentrated and diluted solutions flow through the spaces between the membranes, with the brine flow alternating with the flow of diluted solutions. Electrode rinse solutions flow through the compartments adjacent to the electrodes, and these electrode solutions might be any concentrated solutions of selected electrolytes. Since there is a difference between the chemical potentials of the salt ions in the concentrated and the dilute solutions, then there will be voltages across each membrane which represents an "energy" produced from this technique. This technology was installed and operated in Vladivostok for three years, and it produced up to 4 V (0.15 kWh/m^3) [5], and this process can approach 0.7 kWh/m^3 i.e. more than four times of the amount of energy that has been achieved through the actual operation [1].

Theoretically, the maximal amount of energy that can be harvested from 1m^3 fresh water and a large surplus salt water (30 g NaCl/L) is 2.55 MJ [11–13]. However, transport of large amounts of sea water to and through a RED stack consumes a large amount of energy reducing the energy capability to 1.76 MJ [11–13]. As an example, in the Netherlands, the Rhine has an average flow rate of 2200 m^3/s and has a power potential of 3.9 GW, about 30% of the electricity consumption in the Netherlands [13]. The amount of produced power by RED depends on the availability of the river water and on the energy efficiency of the process. The process efficiency has found been found to be between 14% and 35% [13]

3.2. *Pressure-retarded osmosis (PRO)*

The pressure retarded osmosis (PRO) process has been investigated since the 1960s as a potential process for power generation and, at present, is the most promising method for energy exploitation [3]. This technique can be viewed as an intermediate process between forward osmosis (FO) and reverse osmosis (RO) technologies, because in the PRO process, the hydraulic pressure is applied in the opposite direction of the osmotic pressure gradient (i.e. similar to RO), however, the net water flux is still in the direction of the concentrated solution (i.e. similar to FO). It utilises the osmotic pressure difference between concentrated and diluted solutions to pressurize the concentrated stream, thereby converting the osmotic pressure of the concentrated solution into a hydrostatic pressure that can be used to produce electricity.

The principle of this technique can be displayed in a simplified schematic diagram of power generation by PRO as illustrated in Fig. 2, and it shows that the di-

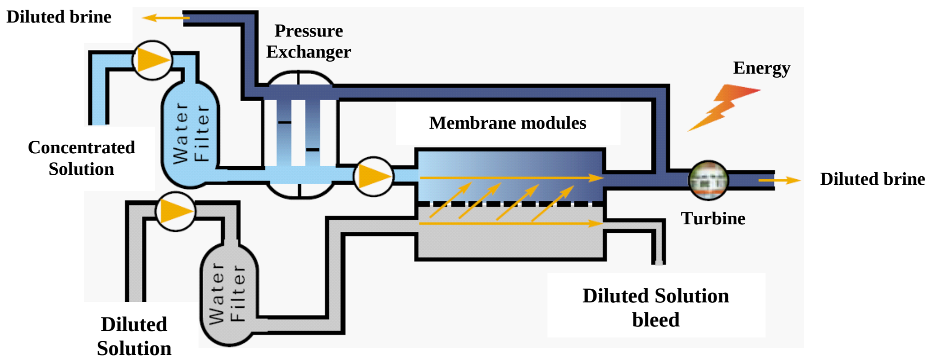

Fig. 2. Simplified process layout for a pressure retarded osmosis power plant [3].

luted solution is pumped into membrane modules (such modules could contain spiral wound or hollow fibre membranes). Over 80% of the diluted solution flows and diffuses across the membrane into the pressurized side of the membrane filled with concentrated solution (i.e. brine). It is important to state that the gross energy gain of this process is the pressure difference multiplied by the volume passing through the membrane. In other words, the osmotic process increases the volumetric flow of high pressure water and this is the key of energy transfer in the PRO process. The diluted and pressurized brine is then split into two main streams; about 1/3 of the water goes to the turbine to generate power, while the rest of water (i.e. 2/3) return to the pressure exchanger to pressurise the incoming feed water (i.e. concentrated solution) [3–7]. Statkraft, one of the main promoters of PRO technology, have analysed the osmotic power exploitation potential, utilising a hydrology based methodology and have estimated the total potential for osmotic power to ca. 1655 TWh [3]. In comparison in 2003, 2645 TWh of hydropower is utilized globally [3].

3.3. Vapour compression (VC)

The energy from a salinity gradient can be generated through a thermal process (i.e. vapour-pressure difference utilization by using vapour compression techniques), and the first proposal of this system was made in 1979 by Olsson et al. [8]. The process exploits differences in vapour pressure of diluted and saline water to obtain power from the gradient in salinity through a difference between the chemical potentials of the salt ions in the concentrated and diluted solutions. A diluted solution is evaporated under a vacuum and condensed in the compartment of seawater. The vapour flow then drives a turbine. According to Jones and Finley [1], the turbine conditions are analogous to the open cycle ocean thermal energy conversion (OTEC). The attractiveness of utilizing this technology (i.e. vapour pressure differences) is that it eliminates the associated problems with membrane technologies (i.e. RED and PRO) [1]. Moreover, this technology does not require a pretreatment system and is highly reliable particularly if the thermal vapour compression technology is utilised. The main advantage of this technology is related to the capital cost (i.e. low construction costs) because of materials selection (such as hydrophilic plastic evaporation condensers and non-metallic vacuum chamber), components design (compact compressors and highly efficient ejector), and low construction costs [1]. Olsson has analysed the osmotic power exploitation potential by installing and testing a laboratory bench-scale testing (i.e. using reversed vapour compression technique), and the experimental data showed that the total potential for osmotic power is 7 W per 1 m^2 of heat exchanger surface at operating temperature of 40°C [8].

3.4. Hydrocratic generator (HG)

A patented technology known as the hydrocratic generator (HG) is another alternative technology in utilising salinity gradient power, and this system was made in 2007 [9]. This invention relates to hydraulic power generation systems and, in particular, to an apparatus and method for generating power using an osmosis phenomenon which efficiently utilizes the osmotic energy potential by mixing two solutions having different salinity concentrations. This technology eliminates the use of any type of membrane and it has the capability to recover energy from a wide variety of environments [1,9]. As depicted in Fig. 3, the patented system consists of three main components which includes; a fresh water injection system (1), an open vertical tube immersed in the water column (2), and a means to extract the energy such as an underwater turbine (3) and deliver the power to shore.

In this process, a diluted solution is introduced into the bottom of the vertical tube, which is conducted through a tube from a reservoir on shore. The diluted solution is then in direct contact (i.e. mixed) with the concentrated solution and enters an enclosed second tube to form a mixture. The second tube, which is known as the "vertical tube", is a cylinder in which fluid is in contact with the source of relatively high salinity solution through

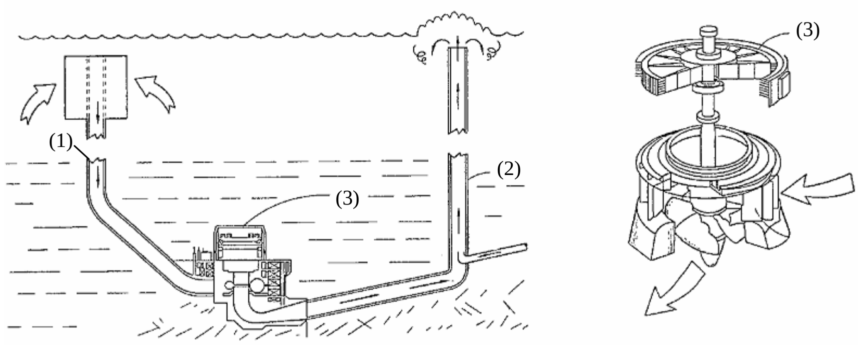

Fig. 3. Simplified diagram of the patented technology [9].

one or more openings [1]. Contact with the higher salinity solution causes entrainment into and up-welling of the mixture within the vertical tube [1]. According to the inventors [9], this technique generates power using a process, which efficiently exploits the osmotic energy potential.

Based on the calculations which have been performed by the inventors (using van Hoff's formula for osmotic power and Pascal's law), in principle, the hydroelectric generator (at 100% efficiency) can generate 1.4 kW of electrical power from remixing one kilogram of fresh water into saline ocean water. However, the experimental data showed that the patented apparatus has achieved 4 kW per 1 m^3 of fresh water per 1 s [9].

4. Utilization of concentrated waste brines for power generation

When an industrial plant (which produces brine effluents) is located in an area where disposal of the brine into a large body of relatively dilute solution is a possibility (i.e. ecologically permissible), then several novel ideas for the application of PRO plants can be explored. Several different types of large bodies of dilute water into which the brine can be disposed are considered; river water (with an average TDS of 300 ppm), Normal Ocean seawater (35,000 ppm), Arabian Gulf seawater (46,000 ppm), and municipal wastewater (10,000 ppm).

Another novel idea for the brine disposal process using salinity gradient power that can be introduced in this paper is that the osmotic power plant can be integrated with Multiple-stage flash distillation (MSF) plants in the Arabian Gulf area. In principle, the water production in Kuwait depends totally on MSF plants, which produce large volumes of distilled water with an average TDS of 5 ppm. In order to comply with the World Health Organisation (WHO) limits for human consumption, the product water should be in the range of 50–500 ppm. Therefore, brackish water is mixed with the distilled water in order to achieve the desired quality of product water. However, this method consumes large volumes of natural resources of water (i.e. brackish water), since the amount of brackish water added to the distilled water reaches approximately 6,810,424 Imperial Gallons (MIG). This is 7–8% of the total fresh water production. Furthermore, this process consumes energy for purifying the brackish water, water delivery, and mixing process (with distilled water). Hence PRO may be incorporated into this process to gain some energy by mixing the distilled water with the concentrated solution which is either MSF brine (70,000 ppm) or groundwater (5,000 ppm). Although the MSF brine is an attractive solution for the osmotic power plants, because with more concentration of concentrated solution, the energy production will increase significantly, its chemical composition may restrict the application because the quality of the product water (which will be produced from the mixture of MSF brine and distilled water) is not in the range desired for drinking purposes. Therefore, if the MSF brine can be treated in order to be used as a concentrated solution for the osmotic power plant, then the outcome would render several benefits to desalination and power plants including; conservation of natural waters, the energy consumed during the normal procedure (i.e. the energy being used for the conventional water treatment process) will be eliminated and a significant amount of energy can be generated. Furthermore, by utilising the MSF brine in an osmotic power plant, the waste stream of the MSF plants will be decreased. The benefits of using groundwater as a concentrated solution in the osmotic power plant are; the consumed energy of the conventional process will be eliminated, and a significant amount of energy can be produced.

In addition to the above ideas, it is well known that the main disadvantage of implementing zero liquid discharge (ZLD) using the thermal approach for disposing the brine is correlated with the economical feasibility, which is likely to be relatively expensive in energy consumption for handling large volumes of high salinity brines. However, the energy consumption for this process can be decreased by incorporating two systems utilising alternative energy, which are an osmotic power plant and a solar pond (SP) (for more information about solar ponds see reference [10]). The salinity gradient of solar ponds helps to reduce the energy consumption that is required by the ZLD process, furthermore, this energy (i.e. energy consumption by ZLD) can be reduced once more by using the second of the proposed alternative energy sources (i.e. osmotic power) by producing energy and also diluting the outlet stream of the concentrated solution to a level that can be treated and recycled by using the ZLD process at reasonable cost and with reasonable reliability, while the brine of the ZLD can be rejected to the osmotic power plant and SP.

This technique may be useful for the oil and gas industries because with the osmotic power plant, the concentrated solution (i.e. high saline brine) can be diluted, and therefore the volume of the diluted brines will be increased, hence, the diluted brine can be split into two streams. One goes to the down-hole injection for enhanced oil recovery in the oil production offshore, which means that this method will decrease the salinity of the well, in particular, in oil fields that have been producing for long periods of time, wells may produce hundreds of barrels of brine for every barrel of oil with extreme salinity. The second stream can be used for the SP to take advantage of the thermal energy available prior to being fed into the ZLD process. On the other hand, based on a theoretical study conducted by Bemporad [10], by coupling a PRO permeator to the SP, it is possible to increase significantly its mechanical efficiency.

5. Predicting the amount of energy

The amount of energy available for the above proposals can be predicted theoretically using

$$U = 2000\,RT\left[C_D V_D \ln\frac{C_D(V_C + V_D)}{C_D V_D + C_C V_C} + C_C V_C \ln\frac{C_C(V_C + V_D)}{C_D V_D + C_C V_C}\right] \quad (1)$$

where C is the concentration (meq/m^3), V is the volume (m^3), T is the temperature (K), R is the universal gas constant (J/(mole K)) and subscripts C and D stand for concentrated and dilute solutions, respectively (this equation was developed by Forgacs [5]).

The above equation gives 0.44 kWh for mixing 1 m^3 of seawater (0.5 M) with 1 m^3 of river water (0.005 M) and 4.7 kWh for mixing 1 m^3 of concentrated brine (5 M) with 1 m^3 of river water (all at 25°C) [5]. It can be noted from Eq. (1) that the amount of energy available depends mainly on four variables, which include salinities and volumes of the diluted and concentrated solutions. However, the results obtained are not precise because the salt composition is assumed to be in terms of pure NaCl for simplification purposes [5]. Therefore, the above results are approximate and are only indicators of an ideal system because many factors (such as chemical composition and species, efficiency of osmotic power plant, etc.) may contribute to a decrease in the energy produced in the real process [1,5]. However, Eq. (1) is used for estimating the amount of energy available in this paper.

6. Results and discussion

Fig. 4 shows a comparison of the results of the theoretical amount of energies available by disposing the brine into different sources of diluted solution, at a volume ratio (dilute solution to concentrated solution) of 1. It shows that the energy reached the highest level when the brine is disposed into a river, while the lowest level of energy available can be seen when the brine is disposed into the Arabian Gulf seawater. This is due to the relative concentration difference between the two solutions that are mixed.

Hence Fig. 4 indicates that the energy available is inversely proportional to the salt concentration of the dilute stream, and also it can be observed that the energy available is proportional to the concentration of concentrated solution being used in the osmotic power plant.

As shown below, Figs. 5–8 represent the results for discharging the concentrated solution (which is varied from 100,000–250,000 ppm) into; a river (300 ppm), Normal Ocean seawater (35,000 ppm), Arabian Gulf seawater (64,000 ppm) and municipal wastewater (10,000 ppm), respectively. The volume ratio of dilute/concentrated solution is represented by D/C.

6.1. Utilization of salinity gradient power by disposing the high saline brines into a river

Fig. 5 represents the amount of energy available when mixing a concentrated solution with river water (with an average TDS of 300 ppm). It shows that the amount of energy available is 1.6 kWh for mixing 1 m^3 of industrial brine (100,000 ppm) with 1 m^3 of river water (300 ppm) and 4.03 kWh for 1 m^3 of concentrated brine (250,000 ppm) with 1 m^3 of river water, all at 25°C. The amount of energy becomes 2.51 kWh by increasing the volume ratio to 2 (at a concentrated solution TDS of 100,000 ppm), Moreover, by increasing the volume ratio to 3, the amount of energy becomes 3.15 kWh at the same salt concentrations of the diluted and concentrated solutions.

Therefore, it is revealed that the amount of energy is proportional to the volume ratio, which means that the energy available is proportional to the volume of the dilute solution used. By mixing the concentrated solution (which has a TDS of 250,000 ppm) with river water at volume ratio of 3, the maximum energy available is 8.02 kWh. Hence it is also clear that the energy available is affected proportionally by the salts concentration of the concentrated solution.

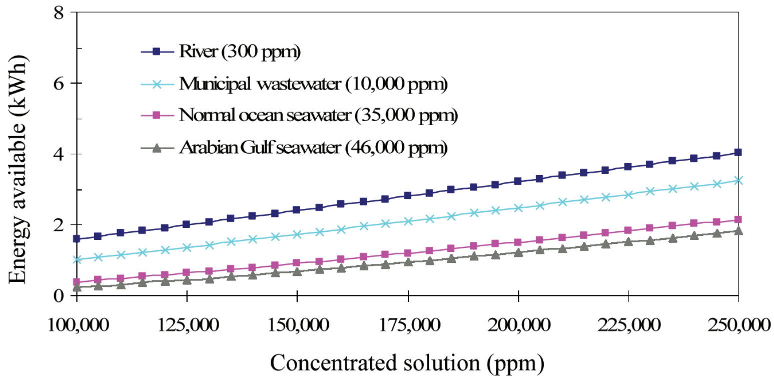

Fig. 4. A comparison of the theoretical amount of energy available when a concentrated electrolyte solution is mixed with different sources of a dilute solution, at a volume ratio of 1.

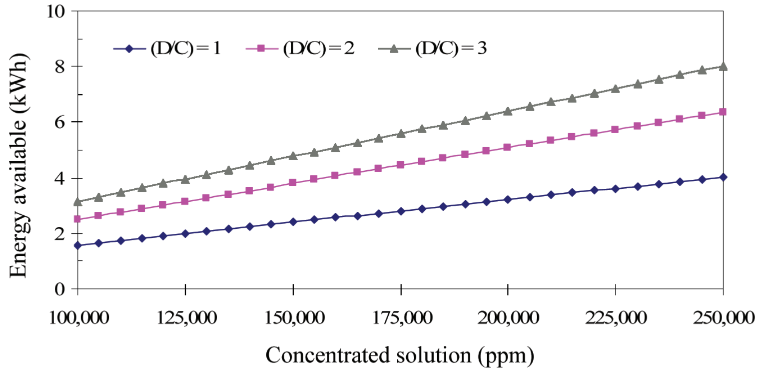

Fig. 5. The theoretical amount of energy available when a concentrated electrolyte solution and river water are mixed at different volume ratios.

6.2. Utilization of salinity gradient power by disposing the high saline brines into seawaters

Figs. 6 and 7 represent the discharge of the concentrated solutions into the relatively dilute solutions of normal ocean seawater and Arabian Gulf seawater, respectively. Fig. 6 shows that the maximum and minimum energies available (at a volume ratio of 1) are 2.15 and 0.38 kWh, respectively, for the mixing of normal ocean seawater (35,000 ppm) with two different salts concentration of concentrated brine (i.e. 250,000 and 100,000 ppm). As shown in Fig. 7, the maximum and minimum energy available decreased to 1.82 and 0.24 kWh, respectively if the concentrated solutions are mixed with the Arabian

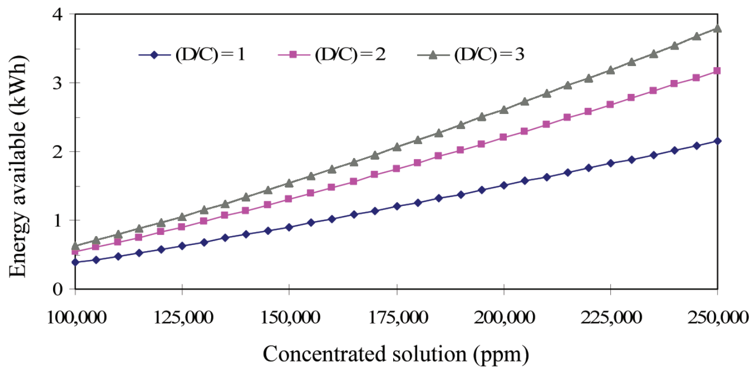

Fig. 6. The theoretical amount of energy available when a concentrated electrolyte solution and normal ocean seawater (35,000 ppm) are mixed at different volume ratios.

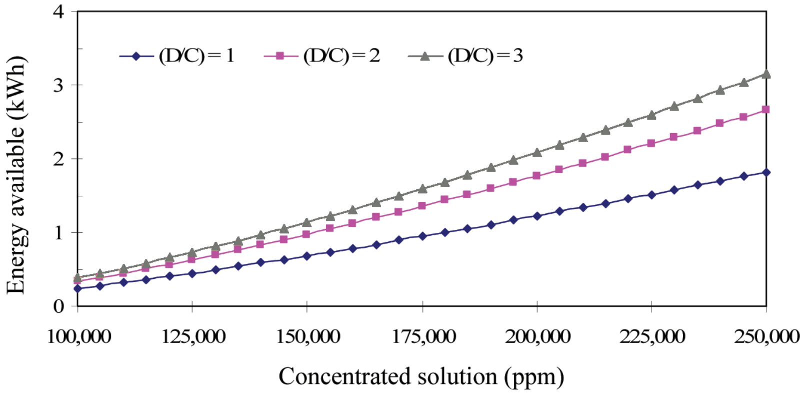

Fig. 7. The theoretical amount of energy available when a concentrated electrolyte solution and Arabian Gulf seawater (46,000 ppm) are mixed at different volume ratios.

Gulf seawater. The reason is that the salts concentration of Arabian Gulf seawater is higher than in normal ocean seawater.

6.3. Utilization of treated municipal waste effluents for power generation

The most common procedure to dispose of municipal wastes of large metropolitan areas located at or near to the ocean shore is to dispose of this waste after secondary or tertiary treatment into the ocean. If this effluent is fed to the industrial brines (i.e. extremely high saline water) or the ocean through an osmotic power plant (i.e. RED or PRO), electrical power may be generated. Incorporation of such a system into the "Iona Waste Treatment Plant in Greater Vancouver" could result in an average power gain of 1–2 MW [5]. The method discussed here could also have another benefit from the intimate mixing, which is less ecological impact near the outfall.

Therefore, by assuming that the municipal wastewater is used as the dilute solution, then it is expected that the amount of energy available will increase. The results of the mathematical calculations of the amount of energy available for such an application are shown in Fig. 8. This shows that the results for the maximum and minimum amount of energy available (at volume ratio of 1) are 1.01 and 3.24 kWh, respectively. Whereas the maximum energy available that can be generated at volume ratio of 3 reaches 6.11 kWh, and by reducing the volume ratio to 2, the maximum energy available becomes 4.98 kWh in such an application.

6.4. Utilization of MSF brine (or brackish water) for power generation

Theoretically, the amount of energy available when mixing brackish water (5,000 ppm) with distilled water (5 ppm) to produce pure water with TDS of 500 ppm (which is desired for drinking purposes) is 0.28 kWh at volume ratio of 10. On the other hand, by mixing the concentrated brine (i.e. MSF brine) with distilled water (at volume ratio of 1), the energy available is 1.14 kWh. However, in order to produce pure water with TDS of 500 ppm from concentrated solution (i.e. MSF brine) and distilled water, then the volume ratio should be 140, and the energy available becomes 8.06 kWh for such an application.

6.5. Practical considerations

As mentioned in section 5, the results produced here are theoretically simplified as the salt composition is assumed to be in terms of pure NaCl. Scaling, i.e. the precipitation on working surfaces of salts due to the concentration process, is always an important consideration for design of plants utilising concentrated salt solutions. As the concentration increases, the potential for scale formation also increases. Fouling of heat or mass transfer surfaces can greatly reduce the capacity and efficiency of a process. The salt solutions used in real processes are also not pure NaCl and contain a mixture of salts. Typically, calcium salts, and in particular $CaSO_4$ and $CaCO_3$, are major concerns [16]. The chemistry of the specific water that will be treated also needs to be understood. For example, halite crystals have been seen to form spontaneously in the Dead Sea due to the increase in salt concentration at the lake surface [17]. Scaling can be limited by various techniques including limiting the operating temperature (calcium salts tend to have retrograde solubility), chemical pretreatment (e.g. the addition of acids or polyphosphates) to alter the solubility or onset of precipitation of scale formers, and lime or lime-soda softening to remove potential scale formers [16]. The PRO and RED processes can be adversely affected by high salt concentrations as these solutions have been shown to permanently damage the membranes [4].

Other practical concerns such as membrane performance and process efficiency also need to be considered. For example, in order for PRO to be competitive, the

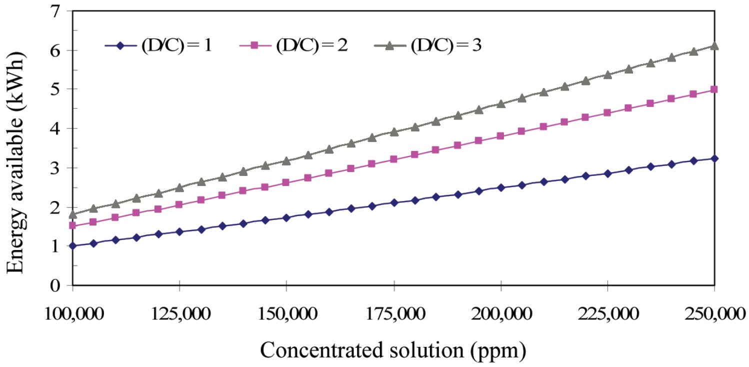

Fig. 8. The theoretical amount of energy available when a concentrated electrolyte solution and municipal wastewater (10,000 ppm) are mixed at different volume ratios.

process requires membranes with high flux and salt retention properties and a production capacity equivalent to at least 4 W/m^2 [15]. A recent study has shown that cellulose triacetate membranes have given power densities close to this value (2.7 W/m^2 and 5.1 W/m^2 for 35 g/L and 60 g/L NaCl draw solutions respectively) [14]. A more rigorous theoretical model for the membrane performance was also developed which takes into account concentration polarisation [14]. The highest power density obtained for RED membranes is 1.2 W/m^2 [13].

7. Conclusions

The important findings from this paper show that it is possible to recover a significant amount of energy prior to disposal of the brine by using an osmotic power plant as a duel system since there is a huge potential to obtain clean energy through salinity gradient power by mixing and disposing of the brine into a large body of dilute solution. This paper showed that this process has many advantages over other brine disposal processes using desalination technologies, especially, in the energy consumption that is required by any treatment system for treating the high saline brine. Also, it should be noted that there is no restriction for applying this technique because, technically, the source of energy is completely renewable, and sustainable, while ecologically, the process is clean and green because it does not produce CO_2 or other significant effluents that may interfere with the natural climate.

With regard to the osmotic power process, several concepts which use a salinity gradient were reviewed, and it is found that the PRO process is the most promising method for energy exploitation. This study also showed the potential power available when mixing concentrated brines with different sources of a large body of dilute solution. In general, the assessment of the analytical solutions showed that the energy available is directly affected by the salt concentrations and volume ratio of concentrated and diluted solutions.

The application of this technology depends mainly on site specific and environmental impact which is related to the effluents of the concentrated solution. Therefore it can be concluded that the application of this disposal method depends mainly on the possibility of dumping the brines into a large body of diluted solution. Hence, when this procedure is environmentally feasible, then the osmotic power plant might be competitive with other brine disposal processes.

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