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Energy aspects in osmotic processes

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ABSTRACT

Water, energy and environmental issues are on the top list of the world problems. Energy is needed for augmenting our water resources. Renewable energies are hardly the answer since innovative techniques based on biofuels and biodiesel consume an incredible amount of water. The modern desalination techniques in use consume different energy levels from different sources. Thermodynamics sets the absolute minimum limit of the work energy required to separate water from a salt solution. Unavoidable irreversibilities augment the actual energy consumption. Modern desalination techniques have succeeded in narrowing considerably the gap between actual and minimum energy levels. The implication of this small gap is that only marginal energy reductions are possible. Energy consumption of different desalination processes are reviewed. Forward osmosis is shown to be a high energy consumption process. It offers, however, advanced cost effective backwash techniques. The limitations of power generation by osmotic processes is discussed. Sidney Loeb together with Sourirajan were the pioneers that opened the door and introduced the RO process that allows us to desalinate seawater and brackish water at affordable energy consumption. Loeb continued during his last years to develop the osmotic energy machine, and even tried to develop an air condition system based on water evaporating from tubular membranes.

Keywords: Desalination; Energy; Reverse osmosis; Osmotic processes; Forward osmosis; Osmotic backwash

1. Introduction

Water shortage is a problem facing many countries. It is widely recognized that alleviation of water shortage in arid regions depends on the availability of affordable desalination processes. Loeb and Sourirajan [1,2] contributed the most significant step in the establishment of a viable desalting technology by developing the high flux reverse osmosis (RO) membrane.

During the last 60 years, several desalination techniques have received wide acceptance as reliable technologies; their rate of growth is impressive, exceeding 12% per year. The fastest growing technique for treating different types of water is the modern reverse osmosis technique. In locations where energy is not an issue, the multi-stage flash distillation is still the most common technique. Multi-effect distillation and vapor compression have a vast potential for competing with MSF for resort areas, and small residential or industrial sites. Many techniques such as the freezing method and solar stills have proved to be inefficient and too expensive.

Some of the old failed attempts to produce cheap water keep on reappearing as novel inventions purporting to challenge the proven well-established techniques. With the continuous water and energy crisis the world is facing, the questions of how much energy is needed to make wa-

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ter, as well as how much water is needed for production of new sources of energy are of wide concern. Research and development efforts often neglect to pay sufficient attention to available literature of the American Office of Saline Water (OSW) during the fifties, sixties and the early seventies. The main objective of this paper is to clarify issues related to energy aspects of membrane processes.

2. Water, energy and the environment

The late Nobel Laureate, Professor Richard Smalley, presented a list entitled "Top Ten Problems of Humanity for Next 50 Years" [3]. His list, in order of priority, is as follows:

1. Energy
2. Water
3. Food
4. Environment
5. Poverty
6. Terrorism and war
7. Disease
8. Education
9. Democracy
10. Population

At the Tuskegee University 79th Annual Scholarship Convocation/Parents Recognition Program he made the following statement, urging his audience to take seriously their role as the higher species on this planet [4]: "We are the only species that can destroy the Earth or take care of it and nurture all that live on this very special planet. I'm urging you to look on these things. For whatever reason, this planet was built specifically for us. Working on this planet is an absolute moral code. ... Let's go out and do what we were put on Earth to do."

The future of humankind will no doubt, be affected by the above list with emphasis on the three interrelated major endeavors — water, energy and environmental protection. Energy, in most conventional forms of electricity production requires water for cooling purposes, and on the other hand, good quality water is needed for growing biofuels and for biodiesel. Food costs have already increased worldwide due to intensified biofuel consumption, affecting especially living conditions of inhabitants in Third World countries. Air pollution and global warming are results of burning oil or biofuel for energy generation, increasing problematic environmental effects. Improper water usage through uncontrolled squandering and neglect of wastewater reclamation are intensifying water pollution and water shortages. Understanding of real energy consumption in water desalination processes is essential for the scientific community as well as for the decision makers.

3. Minimum energy for separation

The concept of minimal energy for separation process is well established in thermodynamics. A theoretical analysis of the minimal energy requirement of some desalination processes has been described by many researchers [5–10]. The minimum isothermal reversible work of separation W, at a temperature T, which is applicable to any desalination process regardless of the separation mechanism is given by [5]:

$$-W = \Delta H - T\Delta S = \Delta F \tag{1}$$

where ΔH represents the change in enthalpy between the final and the initial stages, ΔS represents the changes in entropy, and ΔF is the change of the free energy. Substituting the free energy relations to molar concentration of the salt in water results in:

$$-W = \int \Delta F dn = \int RT \ln a_w dn = \int_{n_1}^{n_2} RT \ln \frac{p}{p^0} dn \tag{2}$$

where n represents the number of water moles in the solution, R is the gas constant, a_w is the water activity in the solution, 1 and 2 represent the initial and final stages of water separation from the solution, respectively, and P is the water vapor pressure assumed as an ideal gas.

The final expression for the minimal separation energy is given by:

$$-W = \frac{0.296T}{100 - n_2} \int_{100}^{n_2} \log_{10} \frac{p}{p^0} dn \tag{3}$$

Eq. (3) expresses the theoretical minimum separation energy in kWh/m^3 of water product. The energy needed to separate fresh water at 25°C from an infinite source of 3.5% salt solution (i.e. normal seawater) is 0.79 kWh/m^3. Seawater desalination is carried out at a water recovery of 50%. In this case, the minimum separation energy is 1.09 kWh/m^3. Further information on this topic is discussed in a recent paper [11].

4. Actual energy demand for RO desalination systems

Energy consumption for the reverse osmosis desalination processes has decreased significantly over the past decade. The main advance was due partly to the development of large, high efficiency pumps, reaching a level of above 90% and mainly on the development of energy saving devices which capture the energy stored in the high pressure waste concentrate stream. The energy consumption of RO processes is now close to the theoretical thermodynamic minimum. All other desalination processes require much higher specific energies.

The energy recovery devices are described by different manufacturers in different names such as "turbochargers," "pressure exchangers" or "work exchangers". They are able to recover very efficiently the energy content of the high-pressure concentrate exiting at the end of the membrane module. While the turbines convert the concentrate pressure into the velocity of a jet that spins a wheel, most other devices uses various types of pistons that transfer the pressure of the leaving concentrate stream to the fresh seawater feed. The energy recovered is used either to boost the pressure of the feed to a second stage, or to run a parallel line of membranes treating more water. In the last case an extra pump is needed to elevate the feed pressure by 2–3 bar. Further information on energy recovery aspects is available elsewhere [14].

The two major energy needs for a seawater RO process are for:

- pumping feed water from the sea, conveying the water through pretreatment equipment and discharging the final concentrate to the sea.
- increasing the feed water pressure way above the osmotic pressure of the concentrate flowing through the membrane passage.

Reverse osmosis seawater desalination currently consumes about 3.5–4.2 kWh/m^3 of product in desalting 3.5% seawater at a recovery ratio of about 50%. About 0.9–1.4 kWh/m^3 of water produced are consumed for deep sea pumping of seawater (about 6 meters below sea-level), for minimizing the transfer of the plankton to the plant through sand filtration devices and micro filtration finishers and for the disposal of the concentrate to the deep sea so as to ensure environmental friendly, proper mixing of concentrate with seawater.

The RO process itself, viz. the pressure loss in the water transfer through the membrane, consumes between 2.2–2.8 kWh/m^3, depending on the type of concentrate energy recovery used. When turbines are used to recover the energy stored in the concentrate the RO specific energy is as low as 2.8 kWh/m^3 of product. Devices like pressure exchangers may reduce energy consumption even further to 2.2 kWh/m^3.

Desalination of brackish water or slightly contaminated water consumes less energy, of the order of 1–2 kWh/m^3. However brackish water sources are usually located inland and the cost of environmentally safe disposal of the concentrate may be appreciable [12,13].

The most widely used arrangement of RO membranes in seawater desalination plants consists of long pressure cylinders containing 7–8 membranes connected in series. The first membrane receives the seawater feed through high pressure pumps and contributes a relatively high water recovery. The last membrane receives the concentrate of the previous membrane, and provides the lowest water recovery in the membrane series. The exhausted concentrate, leaving at a pressure slightly lower than the feed, is used to power a pressure exchanger or a turbine connected on a single shaft to the feed pump and to a motor.

In the main mode of operation of a large scale seawater desalination plant (used below for the energy balance analysis of Table 1), the feed is in a once through flow along the membranes through parallel sets of multi pressure tubes. The first membrane is fed with almost twice as much feed water as the last one and the flow of product permeating this membrane is about 6 times higher than the flow product permeating the last membrane.

The difference between the applied pressure and the osmotic pressure representing the driving force is reduced significantly along the pressure tube. Typical numbers are a pressure driving force of 45 bar at the entrance and of 17 bar at the exit of the unit. The frictional pressure drop along the pressure tube is of the order of two bar. If pressure exchangers are applied, the feed water exchanging pressure with the concentrate, may reach a pressure of about 66 bar. In this case, smaller pumps are used to elevate the pressure to about 70 bar. This mode of operation consumes less energy and the average specific energy can go down to 2.2 kWh/m^3, mainly due to the higher efficiency of the energy recovery devices.

Another less consuming energy mode of operation is when the entire desalination process is divided into two stages. The first stage contains about four membranes and is operated at a pressure of around 35 bar. The pressure of the concentrate leaving the first stage is elevated by use of a turbine, activated by the final concentrate of the plant. In this case, the fluid leaving the first stage is pumped by a set of turbine driven pumps to a level of about 65 bar to the second stage. It is possible to use three stages in a similar way of operation. The benefit is a lower pressure drop along the membranes, a lower flux through the first membranes and a lower concentration polarization on the membranes wall. All this leads to some decrease in the product salinity and a slight reduction of the energy consumption. Operating seawater RO plant at a lower pressure may reduce the energy consumed by the high-pressure pump, but more equipment will be required (membranes, pressure vessels, piping, etc) to maintain the same recovery level. If a lower recovery is applied, there is a need for more pumping energy of the feed to compensate for the lower recovery.

For brackish water desalting applications involving low salinity raw waters, such as slightly polluted streams, the energy consumption may be as low as 1 kWh/m^3 of product or less, depending on water salinity and energy recovery availability. Usually, the recovery level is above 70% and the operating pressure is below 12 bar so that energy recovery in those applications may not be necessary. Seawater desalination plants that also remove the boron from the product or plants that reduce further the salt content in the product of the main RO stage use a secondary and up to quaternary stages of low pressure RO. The energy demand in such systems may add between 0.2–0.3 kWh/m^3, depending on the actual operation scheme.

Table 1 shows the energy consumption for different tasks in a large RO plant. Power savings by concentrate energy recovery is illustrated for two alternatives: usage

Table 1
Energy balance, large-scale plant (based on [15])

	Pumps	Flow, m^3/h	Diff. head, bar	Energy, kWh		Specific energy, kWh/m^3 product
				Pump	Total	
Intake	6	2,200	1.0	77	462	0.07
Raw water supply	6	2,200	2.5	192	1,154	0.18
Feed booster	12	1,042	7.7	281	3,368	0.54
Turbine operation for power saving						
High-pressure aggregate:						
Pumps	12	1,042	69.3	2,381	28,567	
Turbine	12	521	73.0	–980	–11,763	
Motors	12			1,444	17,323	2.77
Auxiliary + lighting				400	400	0.06
Total						3.63
Pressure exchangers for power saving (estimate)						
High-pressure aggregate:						
Pumps	6	1,042	69.3	2381	14284	
Pressure exchangers	Depend on size, *n*	6252/n	66.0	—	—	
Auxiliary pumps	6	1042	3.3	132	792	
Motors	12			1,444	15,076	2.41
Auxiliary + lighting				400	400	0.06
Total						3.26

of turbines and usage of pressure exchangers. Recovery by pressure exchangers is somewhat more economical and provides a saving of the order of 0.4–0.5 kWh/m^3. It should be noted that the energy consumption in small RO plants may be higher due to the lower efficiency of small size pumps.

5. The forward osmosis process

The concept of forward or direct osmosis as a practical commercial process has been recognized at least since the 1930's. The history of this process is described in a paper by Semiat [14]. Recently, significant attention is being devoted to a different desalination process, based on osmotic phenomena between two solutions separated by a membrane.

Osmosis allows passage of water through a membrane from any salt solution into a solution of higher salt concentration flowing on the other side of the membrane [16–18]. The modern version of the process is based on the idea of effortless removal of water from the high concentration "draw" solution — the chosen solution of higher osmotic pressure. It is claimed that the process uses a low energy consumption.

Several compositions of the draw solution have been proposed such as a combination of ammonia and carbon dioxide gases in specific ratios which create highly concentrated draw solutions of thermally removable ammonium salts [17,20] or, in a new nanotechnological approach, use of a draw solution of magnetoferritin nanoparticles which has the advantage that magnetoferritin can be rapidly separated from aqueous streams using a magnetic field [16].

The forward osmosis process is shown schematically in Fig. 1. A feed solution of seawater or some other salt solution is fed to a membrane which is in counter flow contact with a draw solution fed to its other side. Water is transferred from the salt solution by osmotic permeation through the membrane thus diluting the draw solution and concentrating the feed solution. The draw solution of Fig. 1 contains ammonium carbonate. Water recovery and chemicals recycling are achieved by distillation of the draw solution, as shown in Fig. 1 [18,20].

Additional costs incurred in this process are as follows:

- Heat energy is required for the separation of the ammonia and CO_2 from the solution and for the evaporation of large amounts of water
- An additional water purification step, such as ion exchange, is required to ensure that the final product contains less than 1 ppm ammonia.

The gas phase containing ammonia, CO_2 and water vapor is adsorbed on part of the diluted draw solution

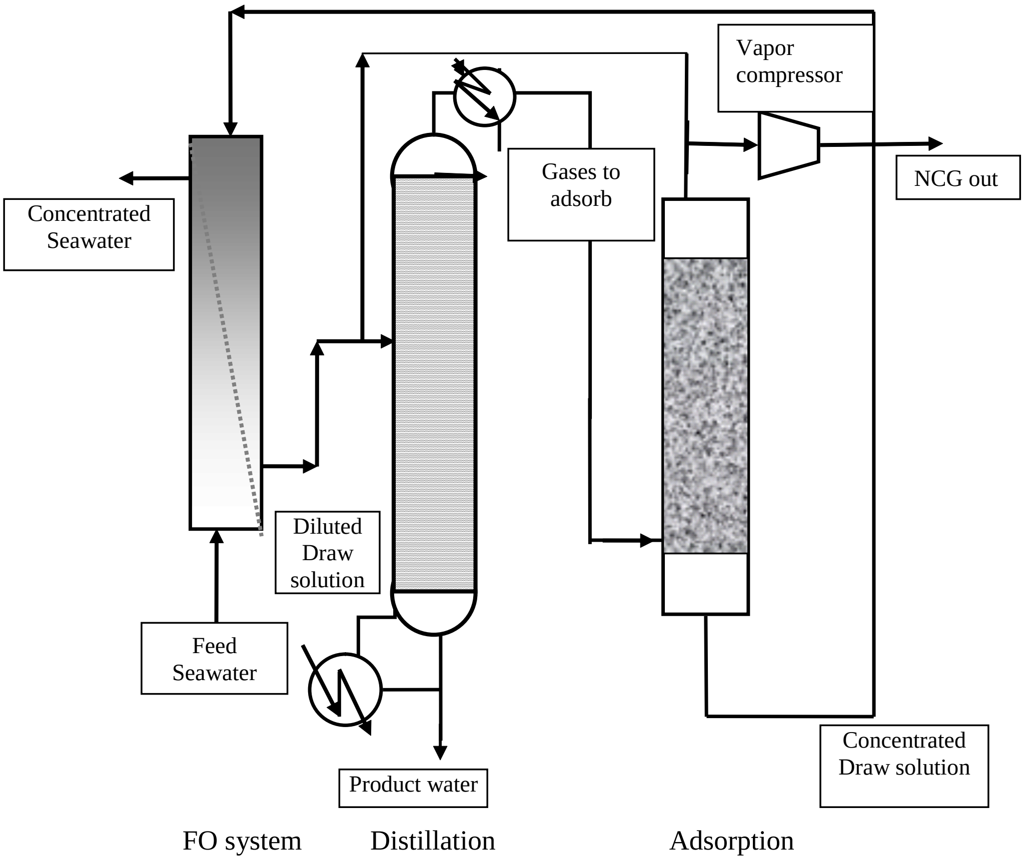

Fig. 1. Basic sections in forward desalination.

to increase its concentration; energy expenses can be reduced by performing the desorption–adsorption at low pressure so as to allow use of low temperature waste heat.

An estimate of the energy consumption of the FO process of Fig. 1 operated at 50% recovery was made using the CHEMCAD simulator. To reduce energy costs it was assumed that the distillation column obtains its heat from exhaust steam of a power station at an optimized temperature that minimizes costs of the electric power available from the consumed steam. It was also assumed that product water still contains 9 ppm of ammonia which can be further reduced by cheaper techniques, such as ion exchange. The results shown in Table 2 indicate that the specific energy needs of the process are around 13±3 kWh/m^3, about 4 times higher than energy requirements of RO seawater desalination.

Further information on FO processes is available in references [21–29].

6. Backwash of RO membranes

It is well known that the effectiveness of membrane cleaning techniques impacts on the plant efficiency and on the energy consumption. In principle, pressurized water could be injected through the membrane from the permeate side to dissolve or dislodge fouling deposits. The structure of current membranes precludes this simple backwash operation. There is a risk of damaging the membrane by detaching its delicate thin top layer which performs the separation.

The realization that direct osmosis or forward osmosis enables transfer of fresh water through an RO or NF membrane by a simple osmotic process inspired new effective techniques for backwashing these membranes. Osmotic backwash operations can be carried out in several ways:

- *Shut down the feed water occasionally for a short time.* This will allow immediate osmotic backwash of the membrane. Water will penetrate the membrane at fluxes that are function of the local salt concentration along the membrane. More water will penetrate the high concentration locations which are more prone to scale deposition and might dissolve small precipitated on the membrane [30,31].
- *Reduce the operating pressure of the concentrate side of the membrane to a pressure below the osmotic pressure in the system.* Water will penetrate the membrane but the backwash flow rate will be reduced.
- *Allow a wave of highly concentrated solution to pass*

Table 2
Estimated energy needs in the FO process of Fig. 1

Operation	Estimated energy consumption (kWh/m^3 product)	Remarks
Pretreatment and concentrate disposal	1.7	Pumping, filtration, etc. similar to RO plant
Pumping water and draw solutions through the membranes	0.3	
Evaporator distillation energy consumption	3	Electricity charge of 13 kWh per ton exhaust steam
Cooling water at the distillation column	3	Pumping energy requirement
Cooling water for adsorbing draw solution gases	4	Pumping energy requirement
Vacuum pump for non condensable gases removal	4	
Credit for cooling water saved in power station for steam supplied to distillation column	–3	Removal of heat from 250 kg of steam.
Total	13	±20% error estimate

through the feed channel without changing the operating condition. Backwash flow will increase but it is necessary to maintain a stock of a highly concentrated solution for this task [32–34].

- *Increase the permeate pressure to a level that allows back flow.* This pressure should be below the concentrate side pressure on the feed side. Masaaki et al. [36] issued patents on a similar backwash using air pressure from the permeate side. However this requires high pressure piping also on the permeate side of the membrane and this will increase equipment cost significantly.

7. Direct osmosis for energy generation

Loeb [36–43] devoted significant efforts to develop an osmotic engine which generates power from two water sources having different salt concentrations, such as seawater and a low salinity fresh water source. The concept is to expose a membrane to a concentrated salt solution on one side and to fresh water on the other side. The membrane can be of the type of RO, NF or UF, depending on the nature of the dissolved substance. Osmotic permeation of the fresh water to the salty water increases the flow of a high pressure stream that can be used to run a turbine and generate electricity.

The need for a source of fresh water to be supplied with seawater limits the process to locations having abundant fresh waters. It is possible to use an artificial high osmotic pressure solution of a dissolved salt with an NF or UF membrane but the need to recover a special salt or highly osmotic substance may consume much of the generated energy. The most economic alternative is discharge of diluted seawater without any treatment.

Fig. 2 presents a schematic flow sheet of an osmosis energy generation plant. In order to generate power, the concentrated solution needs to flow at a certain pressure along the membrane. Due to the water passage, the flow of the concentrated solution increases while its pressure slightly decreases. As shown below, the net power

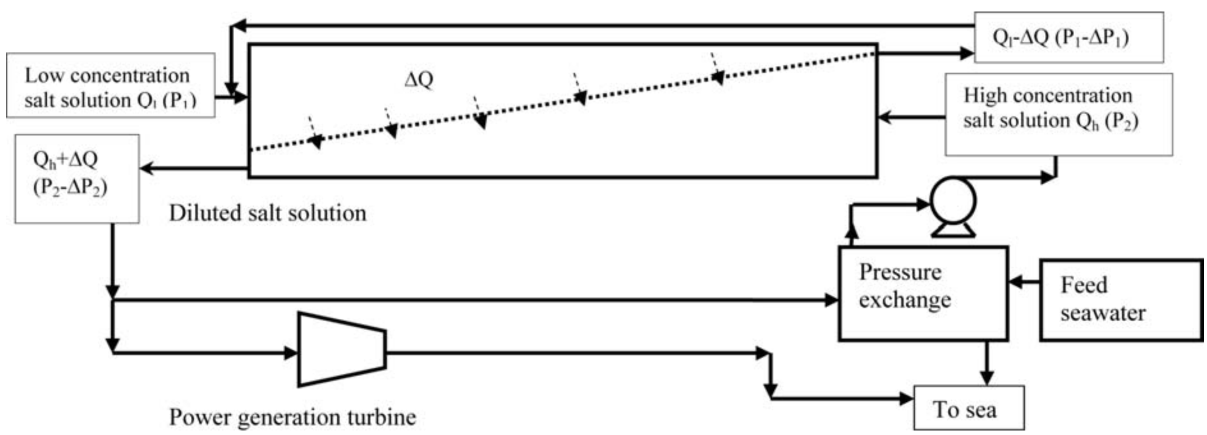

Fig. 2. Block diagram for osmosis energy generation.

(excluding friction) that can be used to run a turbine and generate electricity is proportional to the difference between the product of the pressure and flow rate of this concentrated stream and the product of the initial pressure and initial flow rate of the stream. The energy consumed to pump the solution to and away from the plant has to be subtracted.

For a passage of ΔQ of pure water through the membrane with low pressure drops on both sides of the membrane, the energy ΔE obtained is given by:

$$\Delta E = \Delta Q(P_2 - P_1) - Q_h \Delta P_2 \tag{4}$$

where P_1 and P_2 are the operational pressures across the membrane. The water passage ΔQ is given by:

$$\Delta Q = L_p \left\{ (\pi_2 - \pi_1) - (P_2 - P_1) \right\} \tag{5}$$

where L_p is the permeability of the membrane, and π_1, π_2 are the osmotic pressures in the low and high concentration sides of the membrane respectively. The pressure P_2 should be optimized for high energy recovery and should be between the osmotic pressure of stream at P_2 and the operating pressure of P_1.

The condition for maximum energy generation $\dfrac{d(\Delta E)}{d(P_2 - P_1)} = 0$ shows that

$$P_2 = P_1 + \frac{1}{2}\Delta\pi \tag{6}$$

Hence, the maximum obtainable energy is

$$\Delta E_{\max} = L_p \left(\frac{\Delta\pi}{2} \right)^2 - Q_h \Delta P_2 \tag{7}$$

As regards membrane requirements, Gerstandt et al. [44] report low energy extractions values, below 1.3 W/m^2 of membrane area indicating that very large membrane areas may be required for energy production. Achilli et al. [45] quote a higher energy extraction value from seawater, of the order of 2.7 W/m^2, which indicates the need of about 370 m^2 of membrane area per kWh power generation.

As stated before, the energy available between fresh water and seawater is limited to an operating pressure below the osmotic pressure (about 20 bar for 3.5% seawater), which is of the order of 0.8 kWh/m^3 of fresh water. Since pumping of seawater through a pre-filtration system can consume a few kWh/m^3, power generation with normal seawater may not be economic. Use of a much more concentrated solution such as Dead Sea water which is 8.6 times as salty as ocean water will lead to very high energy production. However, the Dead Sea is located in a desert region devoid of fresh water resources.

8. Conclusion

This paper highlights considerations that need to be taken into account in assessing energy requirements in desalination processes. Careful analysis should be undertaken to include all cost items aside from energy cost. Currently, the lowest energy consumption is achieved by reverse osmosis desalination integrated with energy recovery devices. This energy consumption is remarkably low and not too far from the minimum energy set by thermodynamics.

The energy consumption of a forward osmosis desalination process is high. Forward osmosis has advanced membrane technologies by providing simple cost effective backwash techniques. Limitations of osmotic power generation are discussed.

Symbols

a_w	—	Water activity in the solution
E	—	Energy
H	—	Enthalpy
n	—	Number of moles in solution
P	—	Vapor pressure
P^0	—	Vapor pressure of pure water
Q	—	Flowrate
R	—	Gas constant
RO	—	Reverse osmosis
S	—	Entropy
T	—	Temperature
x	—	Concentration

Subscripts

c	—	Concentrate
f	—	Feed
e	—	Electric
s	—	Salt
w	—	water

Greek

π	—	Osmotic pressure

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