Desalination and Water Treatment
www.deswater.com

23 (2010) 39–48
November

doi: 10/5004/dwt.2010.1857

Fuel cell operated reverse osmosis desalination system

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Received 18 February 2010; Accepted 1 May 2010

ABSTRACT

Kuwait has limited natural water resources and the non-conventional source of desalted seawater is used to satisfy the demand for potable water. Co-generation power-desalting plants (CPDP) are used to produce both electric power and desalted water, with steam extracted from steam turbines to supply desalting units, usually multi-stage flash (MSF) desalting units, with its thermal energy requirements. The MSF system is known for its high rate of energy consumption. The Ministry of electricity and water (MEW) was forced to install gas turbines (GT) to satisfy the increase in the peak load and to carry a good share of the base load. This resulted in a shortage in the availability of steam turbines for future use of the MSF units. Both alternative energy sources (other than steam extracted from turbines) and more energy-efficient desalting systems are needed to meet the rising demands for water and electricity. This paper discusses the feasibility of using reliable and commercially available fuel cells (FC), phosphoric acid fuel cell (PAFC), known as ONSI P25, to operate seawater reverse osmosis (SWRO) desalting system for small communities in Kuwait. The PAFC is known by having documented performance and is operated by natural gas. The SWRO is the most efficient desalting system. The technical merits and the economic benefits involved in combining the PAFC with the SWRO are outlined.

Keywords: Fuel cell; Cogeneration power desalting plant; Fuel used for fuel cell; Reverse osmosis desalting system; Methane; Natural gas; Phosphoric acid fuel cell PAFC; Specific mechanical (electric) energy consumption SEC

1. Introduction

Kuwait has very limited (or barely any) natural water resources. Desalted seawater is the only water resource available to meet the demand for potable water. Desalted water represented more than 90% of potable water in the last few years [1]. The Ministry of electricity and water (MEW), in charge of producing electric power and desalted water to the country, uses only multi-stage flash (MSF) system to desalt seawater. The MSF units are combined with steam turbines in cogeneration power desalting plants (CPDP). Steam is extracted from steam turbines to supply the MSF units with its thermal energy requirement. In each of the main MEW steam power plants (Doha West, Azzour South, and Sabbiya), two MSF units of 7.2 million imperial gallons per day (MIGD) capacity each (or one 12.5 MIGD) are combined with single 300 MW extraction–condensing steam turbine. One million imperial gallons (MIG) is equal to 4546 m^3. This limits the water to power production ratio to 218 m^3 s^{-1} water per MW power and it cannot satisfy the rising demand for water. The rising rate of demand for water is higher than that of power; therefore, more desalted water units with their own power supply are needed. Moreover, the MEW was forced to install gas turbines GT to meet the increase in the peak load and to bear a good share of the base load. As a result, no more steam turbines are available to operate MSF units needed in the future. Both alternative energy sources, other than steam extracted from turbines, and more energy efficient desalting systems are needed to face the rising demand for desalted water. From 1995 to 2005, the produced distilled water increased from 157.2 to 282.8 MIGD (80% increase), while the installed desalting capacity increased from 234.0 to 317.1 MIGD (35.5% increase). The lack of steam turbines (needed to be combined with the MSF units) led to the inability to increase the desalting capacity to meet the demand for water. Thus, any future desalting system, besides being energy-efficient, should be freed from combination with present power plants. The most energy-efficient desalting system is the seawater reverse osmosis (SWRO) desalting system.

There are some merits of using fuel cells (FC) to operate SWRO in Kuwait. The FC has high efficiency and is operated with the available natural gas with less green house gases (GHG) emission than fuel oil. Available commercial FC such as phosphoric acid (PAFC) can be used to supply electricity and heat for many applications such as desalination and air-conditioning.

This paper discusses the feasibility of using PAFC, known as ONSI P25, to operate SWRO desalting systems for small communities in Kuwait and the economic benefits involved. The ONSI P25 has documented performance, and is operated by natural gas. The SWRO is the most energy efficient seawater desalting system. It needs only mechanical (or electric) work to operate. The SWRO is much more efficient than the MSF system. The specific equivalent mechanical (electric) energy consumed (SEC) by MSF is in the range of 20 kWh m^{-3}, while that of SWRO is 5 kWh m^{-3}. Besides full utilization of the fuel cell electric power output, the fuel cell waste heat can be used to pre-heat the feed to SWRO desalting system. The power output of the fuel cell can be connected with the grid and used by the utility to meet the peak load demand, which lasts for few hours only in summer.

2. The phosphoric acid fuel cell (PAFC)

Fuel cells are electrochemical devices that produce electric energy directly from a fuel's chemical energy. The basic block of a fuel cell, Fig. 1, consists of two electrodes (anode and cathode) with an electrolyte in between. Hydrogen fuel is fed through the anode side and gets dissociated to electrons e$^-$ and protons H$^+$. The protons pass to the cathode through the electrolyte while the electrons enter the cathode through an external circuit forming an electric current that can be utilized. When the protons and electrons arrive at the cathode they form hydrogen again and react with the oxygen there. The oxygen is fed to the cathode side as an oxidant and forms water by reacting with the hydrogen.

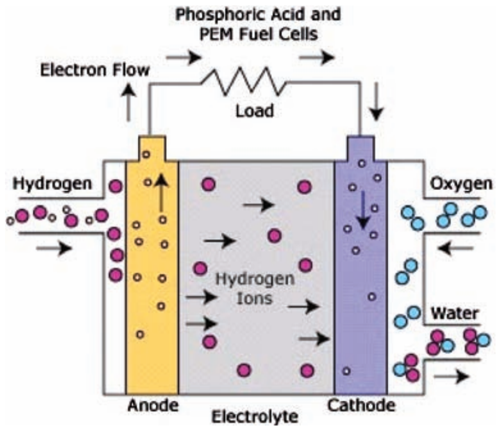

Fig. 1. Schematic of a simplified individual fuel cell [3].

Hence, the equations of the reaction occur in the cell are:

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode: $½O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Cell: $H_2 + ½O_2 + CO_2 \rightarrow H_2O + CO_2$

The anode provides an interface between the fuel and the electrolyte. The cathode provides an interface between the oxidant and the electrolyte. The electrolyte provides a media for the protons to transport to the cathode and prevents the electrons to pass to the cathode. The performance of a fuel cell is evaluated by the product of the current density and the voltage. The actual voltage that can be taken from a fuel cell is less than the theoretical one because of different polarization losses, mainly, activation polarization η_{act}, ohmic polarization η_{ohm}, and concentration polarization η_{conc}.

Fuel cells, as alternative power sources have higher efficiency than conventional power plants (PP). The fuel cells have negligible green house gases (GHG) emissions, since they rely on converting the fuel chemical energy directly to electrical energy, and not on combustion. So, FCs assists in cleaning the environment and can be used to avoid air polluting gases and GHG emissions. FCs are highly reliable, can be maintained easily and have long durability since they do not have moving parts.

Other components included in real FC (see Fig. 2) are:

1. A fuel processor, which consists of a gasifier, reformer, and gas cleaning unit. It converts the fossil fuel (e.g. natural gas) to a hydrogen rich gas. Since hydrogen is not an energetic dense fuel, a fuel processor or reformer is used to obtain pure hydrogen.
2. A power section, which consists of a fuel cell stacks generating (DC).
3. An inverter, which changes DC into alternating current (AC).

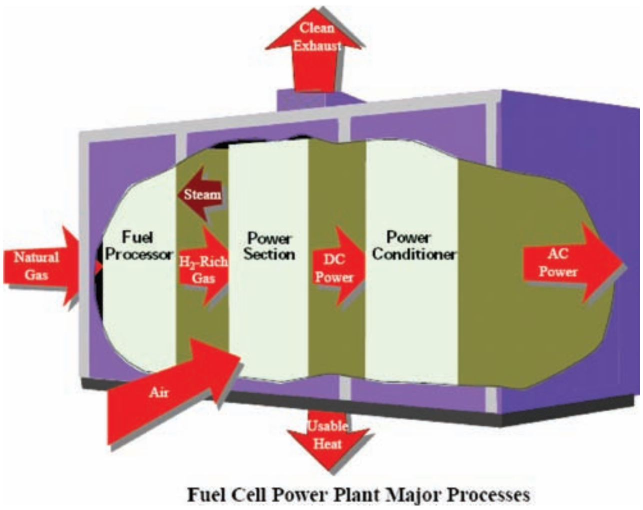

Fig. 2. Schematic of major processes in simplified fuel cell [3].

Steam reformers are used to extract hydrogen from common fuels like methanol and natural gas in PAFC.

The PAFC uses liquid phosphoric acid as an electrolyte [2]. The acid is contained in a Teflon-bonded silicon carbide matrix and porous carbon electrodes containing a platinum catalyst. PAFC is considered the "first generation" of modern fuel cells. It is the most mature type of FC and the first to be used commercially. This FC is typically used for stationary power generation but some PAFCs have been used to power large vehicles such as city buses.

PAFCs are more tolerant to impurities in fossil fuels that have been reformed into hydrogen. They are 85% efficient when used for co-generation of electricity and heat but less efficient (37–42%) when it generates electricity alone. This is only slightly more efficient than combustion-based power plants operating with 33–35% typical efficiency. The PAFCs are also less powerful than other fuel cells, given the same weight and volume. As a result, the PAFCs are typically large and heavy, and are also expensive. PAFCs require an expensive platinum catalyst, which raises the FC cost.

An example PAFC is the commercially available cell known as ONSI P25. It will be chosen for this study. It has 200 kW nominal power capacity and is capable of producing 205 MW of thermal energy.

There is another 400 kW commercial unit of the same type which is produced by the same firm and is known as *PureCell System* and has the following features: it produces 400 kW of assured power, in addition to about 1,700,000 Btu/h of heat for combined cooling, heating and power applications. It is a grid-connected unit, operating in parallel with electric utilities or grid independent unit. It can also run on dual-mode configuration, which enables the unit to operate when grid-connected or independent—switching between modes automatically or on command [2].

3. Reference phosphoric acid fuel cell

The reference PAFC (ONSI P25) considered for operating the SWRO desalting system is the most developed type of FC. Its performance is well documented, it is not very sophisticated, it is more reliable than other fuel cells and should be widely available in the near future. It has 200 kW nominal power capacity and can produce thermal energy of 100 kW at 70°C and 105 kW at 120°C. The cell uses a propylene glycol-water loop to recover the thermal energy which is delivered with built-in heat exchangers for hot water [2]. It has relatively high tolerance to reformed hydrocarbon fuel of rich hydrogen (such as CH_4 natural gas). As an example, natural gas is used by PAFC after steam reforming to provide the FC with H_2 according to $CH_4 + H_2O \rightarrow CO + 3H_2$.

For reforming to take place, the CH_4 and H_2O are to be heated to 538°C or more. This heat is obtained by burning a fraction of CH_4 (about 20%), or burning the partially consumed fuel and air leaving the fuel cell. Excess H_2O is added to reduce CO and to increase the H_2 content (water gas shift reaction):

$$CO + H_2O \rightarrow CO_2 + H_2$$

The reformed fuel contains about 80% H_2 by volume, and the rest is mainly CO_2 with small fraction of CO. The CO_2 as well as CH_4 are electrochemically inert and have practically no effect on the phosphoric acid electrolyte, and this tolerance is the most attractive feature of the PAFC. PAFC uses liquid phosphoric acid, as electrolyte operating at 150–220°C and is contained in Teflon bonded silicon carbide matrix. The small pore structure of the matrix preferentially keeps the acid in place through a capillary action. Some acid may be entrained in the fuel or oxidant streams and additional acid may be required after many hours of operation. Platinum catalyzed porous carbon electrodes are used on both the fuel (anode) and oxidant (cathode) sides of electrolyte. More information on PAFC since its evolution in 1965 is available in reference [3].

The fuel and oxidant gases are supplied at the back of the porous electrodes by parallel grooves formed into carbon or carbon-composite plates, Fig. 3. These plates are conductive and conduct electrons from the anode of one cell to the cathode of the adjacent cell. In most designs, the plates are bipolar in that they have grooves on both sides, one side supplies fuel to the anode of one cell, while the other side supplies air or oxygen to the cathode of the adjacent cell.

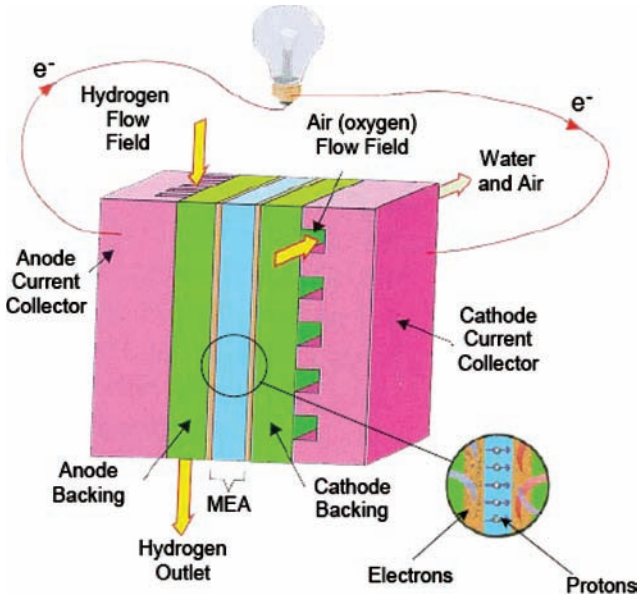

Fig. 3. Schematic of flow details in simplified individual fuel cell [3].

The water byproduct is removed as a steam on the cathode side (oxygen or air) of each cell by flowing excess oxidant past the back of electrodes. The water removal procedure requires operating the system at 190°C. At lower temperatures, the water product will dissolve in the electrolyte and cannot be removed as steam. At 210°C, the phosphoric acid begins to decompose. Carbon plates with cooling channels are provided every few cells to remove the excess heat, Fig. 3. The reaction at the cell is:

$$H_2 + O_2 + CO_2 \rightarrow H_2O + CO_2$$

The reference fuel cell PAFC is employed to provide electric power to run the pumps of the suggested SWRO desalting system. The auxiliary heat from the fuel cell can be used to heat the seawater feed and this increases the permeate flow rate through decreasing the specific consumed energy by the RO process. As the PC-25 is the first available commercial unit, it serves as a model for the fuel cell application. Due to its attributes, the PC-25 is being installed in various applications, such as hospitals, hotels, large office buildings, manufacturing sites, and wastewater treatment plants and institutions. The ONSI P25 has power capacity of 0–200 kW with natural gas fuel, voltage and phasing of 480/277 volts at 60 Hz; or 400/230 volts at 50 Hz. It has thermal energy output of 740,000 kJ/h at 60°C (700,000 Btu/h at 140°F). Its cogeneration module provides 369,000 kJ/h at 120°C (350,000 Btu/h at 250°F) and 369,000 kJ/h at 60°C. It can be grid-connected for on-line service and grid-independent for on-site premium service. The unit dimensions are 3 m (10 ft) wide by 3 m (10 ft) high by 5.5 m (18 ft) long. The unit weighs 17,230 kg (38,000 lb).

4. Seawater reverse osmosis desalting plant design and energy consumption

Reverse osmosis is the most commonly used system worldwide to desalt brackish and sea waters because of its low energy consumption, as compared to thermal desalination systems. The high cost of energy creates genuine interest to lower the energy consumed by large SWRO systems. The specific energy consumed by SWRO ranges from 2.5 to 6 kWh m^{-3} [4]. Besides low energy consumption, other reasons favor the use of SWRO for desalting seawater on MSF method (mainly used in the Arabian Gulf countries), such as, continuous improvements in membrane materials which leads to raising both feed pressure and temperature limits and production of potable water from the high salinity water of the Arabian Gulf in one stage. Moreover, there is no need to combine SWRO with power plant or to interfere with its operation. In fact it can be operated only during non-peak power demand periods. The SWRO has a simple start/stop operation, delivered and operated in modules, without the need to shut off the whole plant for emergency or routine maintenance. Even if the SWRO product has high salinity (say 1000 ppm), it can be tolerated when blended with the Kuwaiti existing MSF distillate output of very low salinity (≈25 ppm).

The main disadvantage of the SWRO is the necessity for extensive feed water pre-treatment, which usually depends on the local waters. Experiences recently gained by using ultra-filtration and nano-filtration solve the main pre-treatment problems.

The energy consumed by the SWRO system depends on many factors such as, feed salinity, temperature, applied feed pressure, recovery ratio (R) defined by the permeate D_p to feed F (D_p/F) ratio, product quality, the efficiencies of pumps and energy recovery devices (ERD), and the membrane type. Calculations of consumed energy by SWRO system for different configurations are outlined here as a guide to evaluate how much seawater can be desalted by the power available from the PAFC. Before that, a brief idea on SWRO system design is presented.

5. Seawater reverse osmosis (SWRO) desalting system for Kuwait

A large SWRO desalting plant consists of a number of trains. Each train has its own high pressure (HP) feed pump supplying seawater feed to a group of pressure vessels containing the membrane elements. The pressure-vessels are connected with permeate and concentrate headers, and instrumented to measure flow rates, pressures and conductivities. Each train is preceded by pre-treatment feed water system and followed by post-treatment for the produced permeate. The pre-treatment, membrane assembly, and post-treatment are designed to supply adequate quality of feed water to the membrane elements, maintain stable performance and produce the design permeate flow and quality, respectively.

The number of membrane elements in each pressure vessel in large desalting system is typically 6 but can reach up to 8. The permeate tubes of the first to the last membrane elements in each vessel are connected to form practically one long permeate pipe inside the vessel. The salt concentration and the osmotic pressure in the feed-brine side of the membrane increase as permeate flows through the membranes and brine flows along each subsequent membrane element. High feed flow rate to the pressure vessel causes high pressure drop and possible structural damage of the elements, while low flow rate of feed-brine creates insufficient turbulence, and thus high concentration polarization, causing excessive salt concentration at the membrane surface. Hence, there are limits to the maximum feed to each pressure vessel and minimum brine flow rate at its exit for a given membrane element type. This information is usually given by the manufacturers.

The first step in the design of the SWRO system is to check the analysis of feed water. This includes its constituent's electrical neutrality and the allowable maximum recovery ratio to avoid scale formation by $CaSO_4$. Typical total dissolved solids (TDS) in Kuwait are equal to 43,313 ppm.

Since the reference PAFC output is 200 kW, its maximum daily electrical energy power production is 4800 kWh. For an average SWRO consumed energy of 4 kWh m^{-3}, the permeate daily output is expected to be in the range of 1200 m^3 d^{-1}. Now, consider an SWRO desalting plant of preliminary 1200 m^3 d^{-1} capacity, using spiral wound membranes known as SW30HR-LE for this process. The membrane, according to the manufacturer test conditions has a specific permeability equal to 1.2 l/(m^2 h bar) and membrane area S = 35 m^2. For flux rate 14 l/m^2 h, feed salinity X_F = 43,313 ppm and the recovery ratio R = 1/3 (calculated according to Kuwait water analysis to avoid $CaSO_4$ scale formation), the brine salinity X_b is 63696 ppm and the average feed brine salinity X_{fb} = 53505 ppm.

The average osmotic pressure of the salty water solution side of the membranes is 41.2 bar approximately. The net driving pressure difference (NPD) required across the membrane to drive the flow is at least 11.67 bar. If the pressure drop per vessel = 2 bar and the permeate side pressure P_p is equal to 2 bar, then a feed pressure of 68 bar is high enough to give the required permeate.

Now different configurations for the SWRO are considered and the specific consumed energy per cubic meter permeate is calculated in order to find the permeate output which can be obtained from the ONSI P25 power output of 200 kW.

5.1. Case A: Simple SWRO train without energy recovery

A simple SWRO system with conventional pre-treatment and without energy recovery used to recover the pressure energy contained in the brine leaving the membranes represents case A. The energy consumed by the high pressure (HP) pump supplying the feed (F = permeate/recovery ratio) at pressure 68 bar, with feed inlet to the pump at 2.7 bar is calculated by:

$$W_{HP,\,pump} = F(m^3/s) \times \Delta P(\text{across the pump in kPa})/(\eta_p \times \eta_m)$$

η_p and η_m are the pump and motor efficiency, respectively. Typical values of η_p and η_m are given in Table 1.

Now for permeate D_p = 1200 m^3/d (13.89 l/s), recovery ratio (D_p/F) = 1/3, where F is the feed:

F = 1200 × 3 = 3600 m^3/d (41.67 l/s), and

Brine rejected B = F – Pr = 2400 m^3/d (27.78 l/s), and by assuming:

$\eta_p = 0.85$ and $\eta_m = 0.95$, then:

Table 1
Typical values of the efficiencies of pumps η_p, motors η_m and energy recovery devices ERD, Ref. [5]

Types of pumps/ ERD	State of the art range %	Selected value range %	Comments
Pumps			
RO First pass			
HP feed booster pump	82–85	84	
HP pump	85–88	87	Depend on capacity
ERD Booster pump	82–84	83	
Permeate intermediate pump	82–85	83	
RO second pass			
Second pass feed pump	84–86	85	
Permeate pump ERD	82–85	83	
Pelton wheel	86–88	88	
Turbocharger	75–83	80	Depend on capacity
Motor and drive	94–96	95	

$W_{HP,\ pump}$ = (13.89/1000) × (6800 − 270)/(0.85 × 0.95) = 336.95 kW

The HP pump specific consumed energy = $W_{HP,pump}/D_p$ = 336.95/13.89 = 24.26 kJ/kg = 6.74 kWh/m^3.

5.1.1. Energy recovery devices (ERD)

The HP pump specific energy of 6.74 kWh m^{-3} for case A is really high. It gives specific energy consumption of 7.5 kWh m^{-3} if the HP pump energy is considered equal to 90% of the total consumed energy. Since the consumed energy is one of the most important factors which affects the water cost, this energy should be lowered.

In case A, the brine leaving the RO membrane, B, has twice the permeate flow rate for 1/3 recovery ratio and its pressure is equal to the feed pressure minus the pressure drop of the feed-concentrate side of the membranes (about 2 bar). So the energy of this brine B = 2400 m^3 d^{-1}, at a pressure of 66 bar, can be recovered by different energy recovery devices (ERD). Turbines were initially applied to utilize the energy of the rejected brine stream to help in the driving of the HP feed pump. The main turbine used as ERD is the Pelton wheel turbine, which is considered in case B. Also a reversed centrifugal pump (working as a turbine) mounted on the same shaft of the HP feed pump (an arrangement known as turbocharger) is considered as case C. Other ERDs include rotary type pressure exchanger (PX) and piston type dual work exchanger energy recovery (DWEER), which are considered later as case D. Selection of the energy recovery system for the SWRO is the deciding factor for the base level of the consumed energy, as shown in the following examples. The efficiencies of the pumps, Pelton turbine or turbocharger are important factors for deciding the ERD performance, see Table 1. The Pelton turbine is well-known for its popular use as ERD in SWRO around the world. It is easy to operate and has low cost. However, it faces hard competition from new generation of ERD, such as, PX and DWEER in big plants since Pelton wheels have less flexibility, limitation of size, and less energy efficiency, as compared to PX or DWEER.

5.2. Case B: Using Pelton wheel

Fig. 4 shows Pelton wheel added to the SWRO system. The energy recovered by this wheel can be calculated as:

$$W_{Pelton} = B(\text{m}^3\ \text{s}^{-1})(\Delta P \text{ across the wheel}) \times \eta_t \times \eta_d$$

where η_t and η_d are the turbine and drive efficiencies respectively. For η_t = 0.88 and η_d = 0.95,

W_{Pelton} = (27.78/1000) × (6600 – 100) × 0.88 × 0.95 = 150.94 kW

Net pumping energy

$W_{HP,\ net} = W_{HP,\ pump} - W_{Pelton}$ = 336.95 – 150.94 = 186 kW

Net HP specific consumed pumping energy = $W_{HP,net}/D_p$ =186/13.89 = 13.39 kJ/kg = 3.72 kWh m^{-3}.

By assuming that the HP net pumping energy represents 75% of the total energy required, the power required to produce 1200 m^3 d^{-1} is 186/0.75 = 248 kW, and the specific consumed energy is 17.86 kJ kg^{-1} (4.96 kWh m^{-3}).

5.3. Case C: Using reverse running pump

A turbocharger arrangement is considered as case C, see Fig. 5. It is the same arrangement of case B, except reversed centrifugal pump (working as a turbine) substitutes the Pelton wheel of case B, [7].The calculations used in case B is repeated here but for a turbine (reversed centrifugal pump) of 0.75 efficiency (lower than that of Pelton wheel).

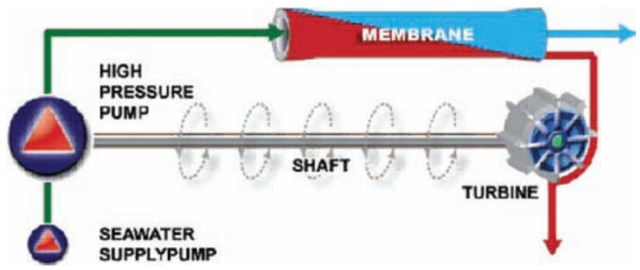

Fig. 4. Schematic of a simplified Pelton Wheel added to simple SWRO train [6].

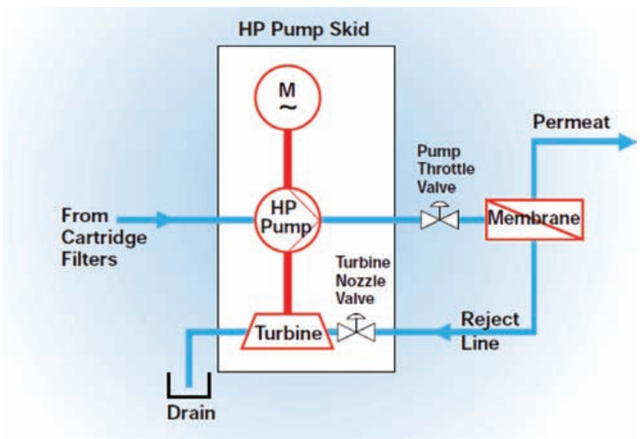

Fig. 5. Case C: where turbine is coupled with the high pressure feed pump.

The energy recovered by the centrifugal turbine is calculated as

$W_t = (27.78/1000) \times (6600-100) \times 0.75 \times 0.95 = 128.65$ kW, when $\eta_t = 0.75$ and $\eta_d = 0.95$, and:

Net pumping energy $W_{HP,\ net} = W_{HP,\ pump} - W_{centrifugal,\ turbine} = 336.94 - 128.65 = 208.3$ kW

Net HP specific consumed pumping energy = $W_{HP,net}/D_p$ = 15 kJ/kg = 4.17 kWh/m^3.

By assuming that the HP net pumping energy is 75% of the total energy required, the power required to produce 1200 m^3 d^{-1} is 277.73 kW, the specific consumed energy is 20 kJ/kg^{-1} (5.55 kWh m^{-3}).

5.4. Case D: Using pressure exchanger (PX) or dual work exchanger energy recovery (DWEER)

To avoid the efficiency losses associated with the energy transformation inherent in Pelton or centrifugal turbines, positive-displacement isobaric devices as energy recovery devices (ERD) were developed and deployed widely for SWRO since 2002. Isobaric ERDs place the RO concentrate reject and low-pressure feedwater in contact inside pressure equalizing or isobaric chambers. Currently, there are two commercially available types of isobaric ERDs including the rotary Pressure Exchanger device and the piston-type work exchanger energy recovery. Both are arranged in the SWRO as shown in Fig. 6, [8]. The high pressure pump is sized to supply only the permeate flow at the feed pressure required by the membrane elements. The membrane rejected concentrate B flows to the ERD. Feed water having the flow rate of the rejected brine B, is also fed to the ERD. The ERD replaces the concentrate with seawater and raises the feed water pressure by the rejected brine. The pressurized feed from the ERD is driven by a circulation pump after raising its pressure to the feed pressure required at the membrane inlet. A small amount of high-pressure water, typically less than 2% of the permeate volume, passes through the seals of the ERD. The HP pump flow and permeate flow remain nearly equal, regardless of membrane feed pressure or booster pump flow rate. Decoupling of the HP pump flow rate and the membrane-feed flow rate allows the system operator to vary the membrane recovery by simply adjusting booster pump flow.

The rotary PX pressure exchanger transfers pressure from the high-pressure brine reject to a portion of feed water by putting them in direct, momentary contact in a rotor. The rotor is fitted into a ceramic sleeve between two ceramic end-covers with narrow clearances that create an almost frictionless hydrodynamic bearing. As the rotor turns, the ducts pass a sealing area that separates high and low pressure. A schematic representation of the ceramic components of a PX device is given in Fig. 7. The SWRO desalting plant in Qadifa and Zaarrah in

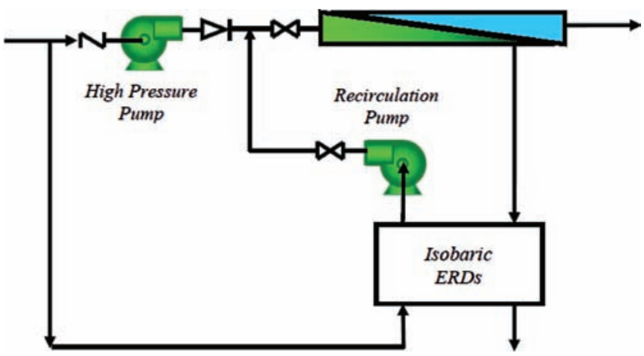

Fig. 6. Isobaric ERD [8].

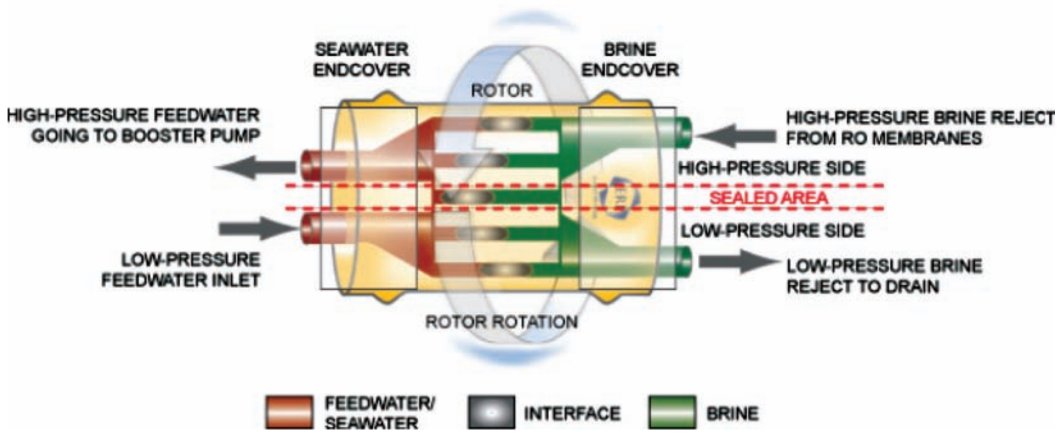

Fig. 7. Schematic of PX flow device [9].

the UAE uses the PX, and this lowers the specific energy consumption to 3.3 kWh m^{-3} for the high salinity water of the Gulf area [9].

The PX rotor contains no pistons or barriers. When the rotor is not spinning, flow passes directly through the device making PX operation during SWRO startup and shutdown almost automatic. Mixing between the brine and seawater streams is limited by the aspect ratio of the rotor ducts which are long and narrow. The PX rotor is designed so that the interface between the brine and seawater never reaches the end of the rotor before the duct is sealed. The largest SWRO trains operating today, 25,000 m^3 d^{-1} (6.6 million gal d^{-1}) in Hamma, Algeria, are supplied with PX devices operating in arrays [10]. The PX energy recovery device mixes about 2% of the high-pressure brine (concentrate) from the membranes with the seawater supply to the booster pump. This flow then mixes with the feed flow from the high-pressure (HP) centrifugal pump. This mixing yields a net increase in salinity of about 2.5%.

The increase in salinity raises the pressure required by the reverse-osmosis membranes by a similar fraction, causing the main HP pump to draw more electric power.

The piston-type devices [11] have large chambers, pistons separating the concentrate and seawater, and valves and control systems to switch flow between the chambers and limit the travel of the pistons as shown in Fig. 8. In the piston type device, there is no inherent mixing of brine and seawater, and if any leakage occurs, it is from the seawater to the brine.

The result is that the water to the membranes is at seawater salinity and the membranes operate at lower pressure, requiring lower pumping power.

Like reciprocating pumps, the positive-displacement pressure transfer mechanism used in isobaric ERDs has high efficiency despite pressure and speed/flow rate variations. As a result, most SWRO plants being designed and built today utilize isobaric ERDs. Many plants built with turbine ERDs have been retrofitted or are considering the conversion to isobaric devices to reduce energy consumption and increase production capacity. An energy recovery efficiency of 98% can be achieved with state-of-the-art isobaric ERDs. Isobaric ERDs can reduce the amount of energy required to desalt seawater by up to 60%, resulting in more economical production of drinking water. The SWRO consumed energy when PX or DWEER is used is around 0.5 kWh m^{-3} less than when Pelton Turbines are used. The PX has higher mixing (increasing the pressure needed in RO) than DWEER but it has lowest losses in Low Pressure and High Pressure circuits.

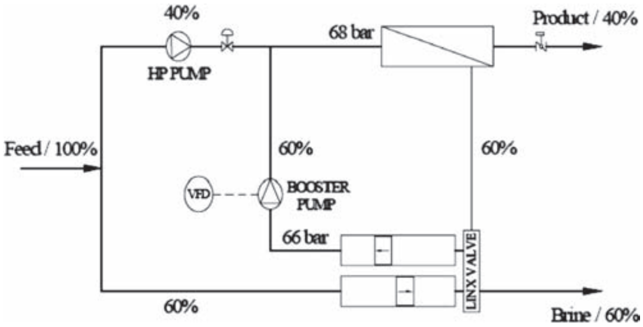

Fig. 8. Schematic of arranging the DWEER (dual work exchanger energy recovery) into SWRO [11].

Calculations of the energy consumed when PX or DWEER is used give almost the same results. By using the same type of calculations performed earlier, the consumed energy by the PX or the DWEER cases is obtained. The volumetric flow rate through the HP feed water pump is equal to the permeate flow; that of the recirculation pump is equal to the brine reject flow. By assuming the same $\eta_p = 0.85$ and $\eta_m = 0.95$, the HP feed pump power input is 112.32 kW and the recirculation pump power input is 13.73 kW, a total pumping power of 125.05 kW. Again if the pumping energy is 75% of the total energy, the required total energy is 166.73 kW, and the specific energy is 3.33 kWh m^{-3}. So, the use of PX or DWEER enables the PAFC to produce up to 1440 m^3 d^{-1}. The results of such calculations are given in Fig. 9.

5.5. Results of cases A, B, C, and D

The results of cases A, B, C, and D are tabulated in Table 2. In this table, the pumping energy is assumed to be equal to 90% of total energy in case A, when no ERD is used, and 75% in all other cases when ERDs are used. It is clear that the most energy efficient case was obtained when PX or DWEER is used. In case A, when no ERD is used, the specific energy consumption (SEC)

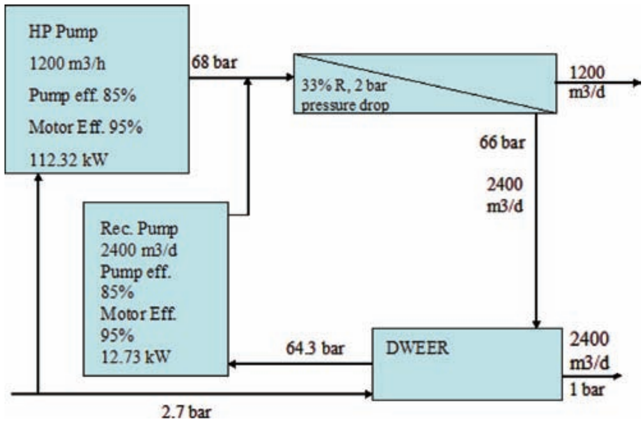

Fig. 9. Energy consumed in Case D when PX or DWEER is used to recover the pressure energy of the membrane reject brine.

Table 2
SWRO desalting plant energy consumption for Cases A–D

Items	Case A	Case B	Case C	Case D
HP feed water pump power, kW	336.95	336.95	336.95	112.32
Rec. feed water pump power, kW	0	0	0	12.73
Turbine recovered energy	0	150.94	128.65	0
Net pumping energy, kW	336.95	186.01	208.3	125.05
Specific net pumping energy, kWh/m^3	6.74	3.72	4.17	2.5
Total required power, kW	374.39	248.01	277.73	166.73
Specific required power, kWh/m^3	7.49	4.96	5.55	3.33

Case A: No energy recovery is used.
Case B: Pelton wheel is used for energy recovery.
Case C: Reversed running turbine is used for energy recovery.
Case D: PX or Dweer is used for energy recovery.
Centrifugal pump efficiency = 0.86.
Motor efficiency = 0.85.
Pelton wheel turbine efficiency = 0.89.
Drive efficiency = 0.95.

was calculated as 7.49 kWh m^{-3}. This decreased 25.8% when reversed turbine is used, 33.8% when Pelton wheel is used, and 55.5% when PX or DWEER is used. This explains the reason many SWRO retrofitting their Pelton wheel with PX or DWEER.

The power output of the PAFC ONSI 25 can produce only 641 m^3 d^{-1} if arrangement A is used (no ERD), 968 m^3 d^{-1} for case B (using Pelton wheel), 864 m^3 d^{-1} for case C (using revesed turbine). In case D (PX or DWEER), the FC power output can produce 1440 m^3 d^{-1}. Thus this makes the specific energy consumption SEC by SWRO equal to 3.33 kW m^{-3} compared to about 20 kW m^{-3} for MSF systems. The number of elements were calculated and found to be equal to 120 and number of vessels are 20. These calculations were conduced for the design at 25°C feed water temperature.

5.6. Effect of fuel cell waste heat on the SEC

The product correction factor when the feed temperature is different than 25°C is expressed by:

$$TCF = \exp\left[U \cdot (1/T_f - 1/298)\right]$$

Here, U is the membrane temperature co-efficient and assumed to be equal to 3020. The temperature increase of the feed due to the waste heat from the fuel cell (205 kW) is 1.23°C. The TCF is calculated and found to be equal to 1.042. This value represents 4.2% increase in the membrane output, or decrease in the power input by 4.2%.

5.7. Economic benefits of owning and operating the fuel cell

5.7.1. The PAFC cost [2,3]

The capital cost of the 200 kW PAFC using natural gas as fuel was $5,500/kW in 1993 and got reduced to $3000/kW in 1996 and it is expected to decrease drastically if PAFC mass production is achieved. The goal for many fuel cell power plants is to reduce their cost to less than $1500/kW. A study by the US department of energy (DOE) considered three costs for the PAFC in the analysis: $660/kW, $750, and $2020/kW and suggested that the last figure is achievable in the very near future. In this study, conservative cost of $2020/kW is used, and this gives the cost of the 200 kW PAFC as $404,000.

While the 200 kW PAFC has standard heat exchanger to provide hot water at 70°C temperature, another high-grade heat exchanger can be added to the cell to recover the high temperature at 120°C thermal energy of 105 kW at a cost of $13,000.

The PAFC fuel reformer is used to convert only one fuel gas to hydrogen. A dual fuel option (propane or natural gas) reformer can be added at the cost of $15,000. To integrate the PAFC power output to the utility, an electrical transformer is needed with an additional cost of $33,000. These raise the cost of PAFC and its auxiliaries to $465,000. Fuel cell degradation will eventually require the stack to be replaced and there will be scheduled and unscheduled maintenance. These will incur additional annual cost of $26,000. So, the total cost of the PAFC with auxiliaries in 10 y is $725,000.

5.7.2. Fuel cost [3]

The 200 kW PAFC uses natural gas as fuel. The minimum HHV of the natural gas is 929 kJ/SCF, where SCF is standard cubic feet of the gas. It was reported that this PAFC consumes 1900 SCF per hour (or 490 kW) and this gives little over 40% efficiency. The cost of natural gas depends on the location. The cost in the US for commercial customers is $5.1/MMBTU (MMBTU is million BTU = 1.0551 GJ) but in other locations where natural gas is available, $3/MMBTU is considered high price. The conservative natural gas cost of $5/GJ (close to the US cost) is used in this study. When the consumed power is equivalent to that of full capacity and 90% of the time 7890 h/y, the PAFC power production in 10 y is 15,780 MWh, (56,800 GJ). If the PAFC efficiency is 40%, the fuel energy needed in 10 y is 142,000 GJ at cost of $710 × 10^3 based on $5/GJ of natural gas. Then the total cost of PAFC and its fuel, operation and maintenance in 10 y is

$1,435,000.00 based on 90% of full time operation, and the cost per kWh is $0.09. Therefore, the energy cost to produce one cubic meter of desalted water by the RO is $0.3 based on 3.3 kWh m^{-3} consumption, as mentioned earlier.

6. Conclusion

A detailed study for using a 200 kW PAFC to operate a SWRO system is conducted. The suggested system is able to produce 1440 m^3 d^{-1}. At the present cost of fuel cell, the energy cost produced by the fuel cell is $0.09/kWh, which is higher than the cost in Kuwait ($0.06/kWh). Also, the environmental benefits of fuel cells should be seriously considered since many of the environmental pollutants associated with combustion-based system do not exist. The given arrangement is more suitable in rural areas where electric power may not be available, and there may be a source of natural gas. Integration of the SWRO with the FC is simple as both can operate with their partial or full capacities. The fuel cell can be connected to the grid when needed during peak hours, while placing on hold or partially operating the SWRO system.

Symbols

C_i	—	Ion concentration
D_p/A	—	Flux rate
FC	—	Fuel cell
K_w	—	Permeability
MEW	—	Ministry of electricity and water
m_i	—	Molar concentration
MIGD	—	Million imperial gallons per day = 4550 m^3/d = 52.662 kg/s
MSF	—	Multi-stage flash desalting system
M_{wi}	—	Molecular weight
PAFC	—	Phosphoric acid fuel cell
P_p	—	Permeate side pressure
P_f	—	Feed pressure
ppm	—	Parts per million
PV	—	Pressure vessel
R	—	Recovery ratio
RO	—	Reverse osmosis desalting system
SEC	—	Specific mechanical (electric) fuel energy consumption
SWRO	—	Seawater reverse osmosis desalting system
SR	—	Salt rejection
TCF	—	Temperature correction factor
TDS	—	Total dissolved solids
T_f	—	Feed temperature
U	—	Membrane temperature co-efficient
W_p	—	Pump energy
W_{pw}	—	Pelton wheel energy
X_B	—	Brine salinity
X_F	—	Feed salinity
X_{FB}	—	Brine feed salinity

Greek symbols

η_p	—	Pump efficiency
η_{pelton}	—	Pelton wheel efficiency
η_t	—	Turbine efficiency
π	—	Average osmotic pressure

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