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CHAPTER XX

Fuel cells as an energy source for desalination applications

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1.1 INTRODUCTION

Nowadays, there is a renewed interest in fuel cell technology from industry and academia, electrochemistry and catalysis scientists. This interest is due to environmental legislations for CO_2 and other greenhouse gases emissions (United Nations Environment Programme and the World Trade Organization, 2009) that demand the use of high efficiency energy production systems. Such systems have great potential in the area of desalination technology (Kenet, 2003, Al-Hallaj *et al.*, 2004, Singh, 2008, Wang *et al.* 2011, Jones, 2013). Fuel cells are characterised by high operation efficiency, which results in decreased fuel consumption, and low environmental impact. A fuel cell is a device that converts the chemical energy of a fuel directly into electricity through electrochemical reactions, with low waste heat (e.g. SOFC in Fig. 1). The first fuel cell was fabricated back in 1830's, and slow but steady progress has been made toward their commercialization since then.

Ensuring access to clean, fresh water is among the major problems faced by the world's growing population (Wali, 2014). A recent report published by the World Resources Institute puts Middle East high in the ranking of World's most water stressed countries in 2040 (Maddocks *et al.*, 2015). According to this report, fourteen of the 33 likely most water stressed countries in 2040 are in the Middle East, including nine considered extremely highly stressed: Bahrain, Kuwait, Palestine, Qatar, United Arab Emirates, Israel, Saudi Arabia, Oman and Lebanon. In general, rapidly growing populations will drive increased consumption by people, farms and companies. However, it is not clear where all that water will come from? Water desalination will therefore play a dominant role in solving water scarcity. SOFC technology is one of the key technological adavancements, which can enable sustaianable water desalination.

As described by Ghaffour *et al.* (2015), Khawaji *et al.* (2008) and Jones (2013), desalination processes require external energy. A variety of desalination technologies have been developed over the years on the basis of thermal distillation, membrane separation, freezing, and electrodialysis. The two most important technologies are based on the MSF and RO processes. It is viewed that three processes, e.g. multi-stage flash (MSF), reverse osmosis (RO), and membrane distillation (MD) will be dominant and competitive in the future (Khawaji *et al.,* 2008, Jones, 2013). According to International Desalination Association (IDA) inventory record, in 1999 approximately 78% of the world's seawater desalination capacity was made up of MSF plants while RO represented 10%. However, there has been a gradual increase in RO seawater desalination primarily due to its lower cost and simplicity (Khawaji *et al.,* 2008). Furthermore, some of the sources like wind turbine, solar thermal systems, photovoltaic (PV), biogas plant and

fuel cell are being widely used for desalination, but they only provide intermittent power (Chittu and Jeyaprabha, 2013). As a result of this problem, the intermittent energy is used to split water in an eletrolyser and use the produced hydrogen to run a fuel cell to provide a backup energy source for desalination purpose (Kenet and Belmar, 2003).

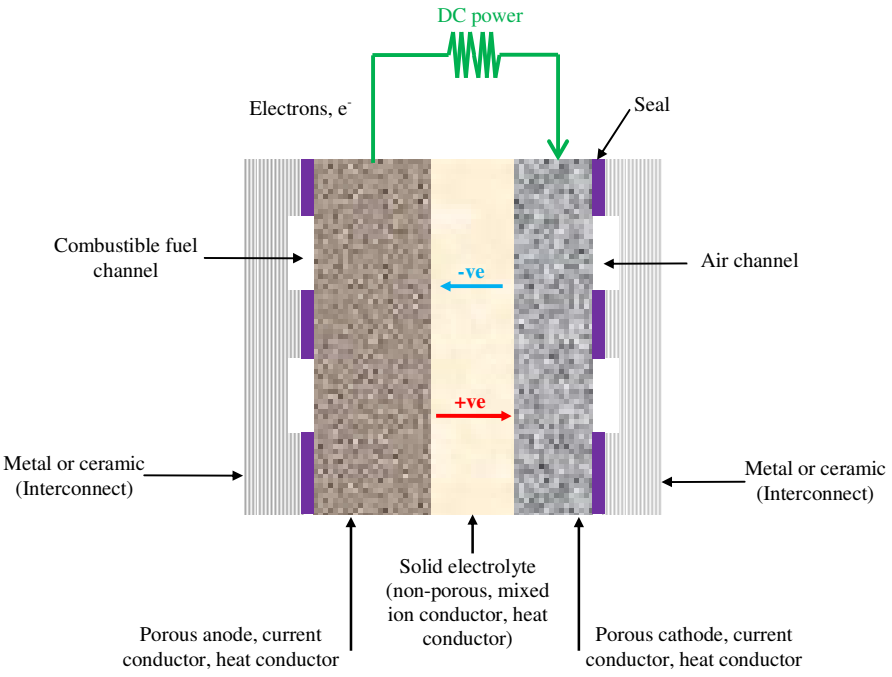

Figure 1. Scheme of SOFC: Fuel is fed to the anode (negative electrode) and an oxidant is fed to the cathode (positive electrode). Electrochemical oxidation and reduction reactions take place at the electrodes to produce electric current. For example, in the traditional SOFC, oxygen (from air) is reduced by a porous cathode producing oxide ions (-ve) which migrate through a solid electrolyte to the porous anode and react with the fuel (H_2, CO, CH_4) forming H_2O and/or CO_2. The electrolyte may conduct either oxygen (SOFC) or hydrogen ions (PC-SOFC). In a PC-SOFC, the reaction product (water vapor) is evolved at the cathode side instead of at the anode (fuel side) as is the case for oxygen ion-conducting SOFC. Hence, no dilution of the fuel takes place in the PCFC, resulting in significantly higher efficiency (adapted from Faisal *et al.*, 2015).

The development of low-cost fuel cell materials with high durability and lower operating temperatures is the key technical challenge facing various fuel cell technologies. The future of fuel cell technology depends upon the development of new materials (electrode/electrolyte) which can be used to manufacture fuel cells in a cost effective manner. Fuel cells present a number of inherent challenges. Low mechanical strength, slow start-up time (i.e. in minutes), and serious anode deterioration represent some of these inherent challenges. The high operating temperatures (800-1000 ºC) place additional durability requirements on fuel cell materials. The development of low-cost materials with high durability at lower operating temperatures is the key technical challenge facing fuel cell technology. Reducing the operating temperature to intermediate range can lower the cost but it also reduces the reaction rate (Shao, 2005). The scope of this section is to summarise fuel cell systems (Table 1) which are actively involved in power generation (i.e. converting the chemical energy of fuels such as natural gas or oil into electrical power).

Table 1. Fuel cell types (these are traditional data but some data compiled from Al-Hallaj *et al.*, 2004, Singh, 2008 and Al-Hallaj and Kiszynski, 2011).

#	Fuel cell type	Operating temperature (°C)	Power ratio (heat:electric)	Energy grade	Electrodes/Electrolytes
1	Solid oxide fuel cell (SOFC)	650-1000	0.67:1	High	Ceramic; Charge carrier: O^-
2	Molten carbonate fuel cell (MCFC)	300-700	1:1	High	Immobilised liquid molten carbonate; Charge carrier: CO_3^-
3	Phosphoric acid fuel cell (PAFC)	80-200	1.27:1	Moderate	Immobilised liquid phosphoric acid; Charge carrier: H^+ (proton)
4	Proton exchange membrane fuel cell (PEMFC)	80-120	-	Moderate	Ion exchange membrane; Charge carrier: H^+ (proton)
5	Direct methanol fuel cell (DMFC)	50-120	-	Moderate	Polymer electrolyte; Charge carrier: H^+ (proton)
6	Alkaline fuel cell (AFC)	50-90	-	Low	Mobilised or immobilised potassium hydroxide; Charge carrier: H^+ (proton)
7	Microbial fuel cell (MFC)	20-40	-	Low	Chemical that transfers electrons from the bacteria in the cell to the anode)

As shown in Fig. 1 SOFCs can take many different forms, but they all share the same basic structure. There will be a solid oxide electrolyte, sandwiched between a cathode and anode. The cathode is typically a thin, porous layer, where oxygen reduction will occur. The electrolyte is a dense ceramic layer which is ionically conductive but electrically insulating. The electrolyte does not typically become ionically active until it is at a temperature between 850 K and 1250 K. The ceramic anode layer is typically a porous layer to ensure maximum contact between the fuel and anode surface, though in this case a molten metal anode is tested. Once the cell is at optimum temperature, spare electrons in the cathode layer reduce oxygen atoms from either the air or an oxygen supply to give oxygen ions. These ions diffuse through the ionically conductive electrolyte to the anode, where they can oxidise a fuel. This reaction produces a combination of water and CO_2 (fuel dependant), as well as electrons. Since the electrolyte is electrically insulating, the electrons flow back to the cathode through an external circuit, where they can do work on a load. This cycle will repeat so long as sufficient fuel and oxygen can be supplied. As summarised by Singh (2008), it is possible to construct a fuel cell of high efficienecy (as high as 80% to 90%). However, in current practice, because of irreversible losses (over-potentials), the efficiency of a fuel cell system is 40% to 45% based on the lower heating value of the fuel. However, efficiencies of 80% have been achieved for fuel cell power plants with cogeneration, i.e. combined heat and power systems, and hybrid fuel cell-reheat gas turbine cycles have efficiencies approaching 70%.

Novel works on the integration of fuel cells with desalination systems are summarised in this chapter. The underlying motivation for such system integration is that the exhaust gas from a hybrid power plant (e.g. fuel cell or turbine) contains considerable amount of thermal energy, which may be utilized for desalination units.

Water is an important resource for all and it is essential for agricultural and industrial growth, as well as for populations who require a safe drinking water. It is known that 97% of all water in oceans, 2% in glaciers and ice caps, and the rest in lakes, rivers and underground (Al-Shayji, 1998). Available fresh water accounts for less than 0.5% of the earth's total water supply (Khawaji, 2008). Natural resources cannot satisfy the growing demand for low-salinity water with industrial development, together with the increasing worldwide demand for supplies of safe drinking water. In the Arab Gulf countries, most power plants are cogeneration plants producing electric power and process heat for water desalination (Al-Hallaj *et al.*, 2004). For a given fuel

input, the production of water in a cogeneration system is associated with a reduction in electrical power. Although, desalination costs have decreased markedly in the last few decades, cost remains a primary factor in selecting a particular desalination technique for drinking water production. Some reduction in desalination costs may be realized from improvement in plant design, fabrication technique, heat exchange material, plant automation, and scale control techniques (Al-Hallaj *et al.*, 2004). Energy cost for distillation plants (steam and electricity) represents at least 40-50% of the cost of water (Lunghi, 2001). The minimum cost of water from seawater desalination occurs when power and desalination are combined in one "dual purpose facility" that simultaneously produces electricity and water (Al-Hallaj *et al.*, 2004).

Unfortunately, many people have limited access to water and energy resources in recent times. In order to solve this dire issue, industry leaders, governments, scientists, and researchers have been developing and improving various technologies that show promise for being able to sustain the demand for energy and water of a growing population (Jones, 2013). It is known that high temperature fuel cells produce electricity and high temperature exhaust gases, which can be used as a heat source for desalination applications (Al-Hallaj *et al.*, 2004). The exhaust gas temperature depends on the fuel cell type and may range from 100 °C to 1000°C. This chapter therefore summarise how fuel cell technologies can be used for desalination purpose and provides the current status and future prospects of some of the combined technologies.

1.2 ENERGY CONSUMPTION IN DESALINATION

According to Jones (2013) and WateReuse Desalination Committee's White Papers (2011), a typical RO desalination plant requires 8.7-9.7 kilowatt-hours of energy per thousand gallons of water processed. This includes water pretreatment and the actual seawater reverse osmosis process, which accounts for the largest amount of energy consumed during the process. Post-treatment conditioning and pre-treatment make up 1-2% of the energy consumed in RO. As summarised by Jones (2013), RO has proved effective in supplying water to regions that lack potable water is desalination. However, this process requires significant amount of energy to produce clean drinking water. This section focuses on the energy consumption and productivity of desalination through cogeneration, e.g. combined heat and power (CHP). Despite success in the commercial realm, desalination is an expensive and energy intensive process. One way to reduce the energy expenses associated with desalination is through the use of alternate cogeneration systems (Jones, 2013). This type of system would combine alternative energy technologies that use low-grade waste heat with a desalination system for heat and electrical energy production. However, with some processes, like RO, requiring chemical pre-processing of feed streams and a large amount of equipment maintenance, the time and money required to maintain a desalination plant, even with the use of alternative technologies, makes desalination a non-feasible process for places with small economies. In an effort to improve the energy efficiency of desalination processes, researchers have been developing and testing desalination plants that combine water treatment and energy production into a single location. The idea behind these combination plants is that the energy efficiency of the desalination process can be increased by using the waste heat and electricity from a separate energy production process to heat the incoming feed streams and power the pumps and auxiliary equipment of the desalination system.

1.3 INTEGRATED AND HYBRID SYSTEMS: FUEL CELLS WITH DESALINATION

The integration means a fuel cell when connected to an energy source for the desalinator and a ‘heat exchanger’ transfer waste heat from the fuel cell to desalinator for the purpose of water

desalination (Ghalavand *et al.*, 2015). The heat exchangers which play a key role in the active integration, may be a tube bundle or coil surrounding the fuel cell and/or its heated water output, and may be made of copper tubing or other heat transfer promoting material. The heat exchanger may also be a concentric counter-flow thin film heat exchanger or a plate-type exchanger may also be possible. There are several case studies involving integration of desalination with reverse osmosis (RO), with thermal multi-stage flash (MSF) and membrane distillation (MD) units. In such examples, the underlying motivation for such system integrations are that the exhaust gas from a power plant (e.g. fuel cell) contains considerable amount of thermal energy, which may be utilised for desalination units.

For example, the high operating temperature of MCFC and SOFC as shown in Table 1, provides an opportunity for using waste heat for desalination units (energy grade source temperature range given in Table 2). Similarly, proton exchange membrane (PEM) fuel cells, which generally operate at low temperatures (about 80-120 °C) are also promising for desalination purpose (Kenet and Belmar, 2003). They also advised that phosphoric acid electrolyte (PAFC), which generates high waste heat, of up to 180 °C or more, and is thus often considered less efficient or practical than membrane fuel cell technology. Although only few case studies are presented in following section, the concept of integrating fuel cells with desalination units should not be not limited to RO, MSF and MD and should have similar benefits with other desalination technologies (e.g. vapor compression cycle).

Table 2. Desalination types and energy grade sources temperature range.

#	Desalination type	Operating temperature or energy grade (°C)	Energy demands for desalination (Al-Hallaj and Kiszynski, 2011)	Reference
1	Reverse osmosis (RO)	4-40	4-5 kWh/m^3 (electric); 4-5 kWh/m^3 (heat);	Al-Hallaj and Kiszynski, 2011
2	Multi-stage flash (MSF)	25-110	4 kWh/m^3 (electric); 14 kWh/m^3 (heat);	Wu *et al.*, 2012
3	Membrane distillation (MD)	20-85	-	Gryta, 2012
4	Multi-effect distillation (MED)	70-80	4 kWh/m^3 (electric); 11 kWh/m^3 (heat);	Bataineh, 2016
5	Multi-effect boiling (MEB)	Up to 70	-	Darwish *et al.*, 2006
6	Mechanical vapor compression (MVC)	Up to 100	-	Ghalavand *et al.*, 2015

Since fuel cell release a considerable amount of waste energy during operation in the form of hot water or steam (Al-Hallaj *et al.*, 2004). This waste energy can be captured by cogeneration systems to improve overall hybrid fuel cell/desalination (HFCD) system efficiency. It is important to know that HFCD system can be more efficient than separate fuel cell desalination system, and the use of excess electricity generated by fuel cells for water desalination can eliminate the need of electricity storage in batteries during off-peak hours (Al-Hallaj and Kiszynski, 2011). Al-Hallaj and Kiszynski (2011) has also suggested that for HFCD system design, the demand for electricity should be given greater significance than the demand for water, as variations in water demand are never as sharp as those in electricity demand and water storage is easier and cheaper than electricity storage. Hence, HFCD systems must be designed based on the peak electricity demand.

The maximum power outputs from the fuel cells can be calculated using simple heat transfer analytical method. The difference between the fuel cell temperature and the desalination temperature will determine the power (Q) that can be exchanged between the cooling air and brine streams, as shown in equation (Al-Hallaj and Kiszynski, 2011), $Q = \dot{m}.C.(T_{FuelCell}-T_{Desalination})$, where $T_{FuelCell}$ is the fuel cell temperature, $T_{Desalination}$ is the top brine temperature of the desalination process, C is the lower specific heat capacity between the water and the air, and $\dot{m}$ is the mass flow rate of the cooling air. These two temperatures and mass flow rate of cooling air are

dictated by what type of fuel cell and what type of desalination unit is used (refer Table 1 and 2). From Table 1, a 1 MW PAFC plant will provide 1.27 MW of thermal power (operating temperature between 80-200 °C). Therefore, the mass flow rate can be calculated from equation (Al-Hallaj and Kiszynski, 2011), $Q = \dot{m}h(T)$, where $h(T)$ is enthalpy as a function of temperature.

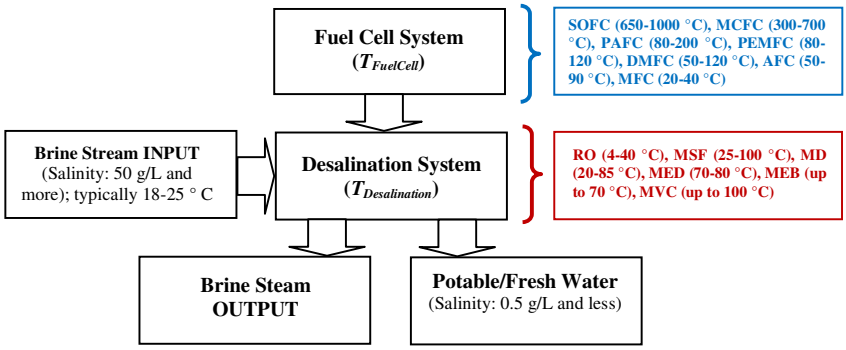

Figure 2. Schematic of integrating fuel cell with desalination system.

1.3.1 Integration with reverse osmosis (RO) desalination unit

Reverse osmosis (RO) is a pressure-driven process (where electricity is used to drive the feed pump, thereby increasing the feed pressure), ranging 50-80 atmospheres, commonly used for water distillation (Khawaji *et al.*, 2008; Lee *et al.*, 2011; Jones, 2013; Bataineh, 2016). In this process, an aqueous solution is pressurised above the osmotic pressure of the solvent. The pressurised solution is then sent through the center of a semi-permeable, spiral-wound membrane, where the solvent passes through the membrane pores to the product collection compartment at the center of the membrane module. Membranes used for RO are typically made from cellular acetate. It is important that the pores of the membrane only be large enough to allow the solvent molecules to pass through. The solution must be pretreated before coming into contact with the membrane. Pretreatment is needed to prevent membrane fouling-surface build-up and pore clogging, which can decrease the usable life of the membrane. Additionally, the spiral-wound design of the membrane only allows one-way flow, which makes it impossible to clean the membrane module of unwanted solids and residues. Typical energy consumption in seawater RO plants operating at 40-45% product water recovery and with energy recovery from the high pressure reject stream is about 3-4 kWh/m^3 (Singh, 2008).

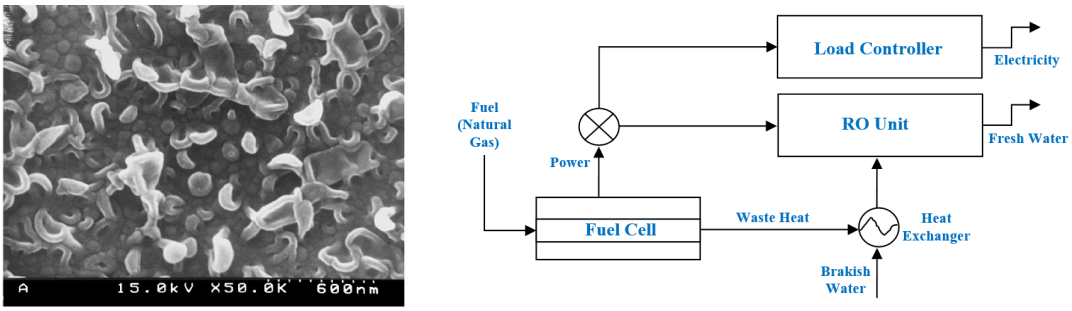

Figure 3. (a) FE-SEM micrographs of RO membranes surface: *m*-phenylenediamine (MPD) in aqueous phase and trimesoyl chloride (TMC) in organic phase (reproduced by publishers permission, Kwak and Ihm, 1999), and (b) schematic representation of a hybrid system combining fuel cell and reverse osmosis unit (adapted from Al-Hallaj, 2004).

RO can work with a low grade of energy source (4-40 °C). Al-Hallaj *et al.* (2004) presented a novel fuel cell/desalination system (Fig. 3), where two types of hybrid system was presented (i.e. fuel cell/reverse osmosis hybrid system and fuel cell/thermal desalination hybrid system). It was shown that by preheating the feed water to the RO system using the fuel cell exhaust gas, the energy demand of the desalination system reduces by 8%.

1.3.2 Integration with thermal multi-stage flash (MSF) desalination unit

As shown in Fig. 4, multi-stage flash (MSF) desalination is a thermal process consisting of a set of *n* stages, each of which operates at a lower pressure and temperature than the previous (Tarifa and Scenna, 2001; Jones, 2013). In this process, a high salinity aqueous solution is fed into the system at stage *n* through the condensing pipes. From stage *n* to stage 1, the solution simultaneously cools the newly distilled water vapor on the outer surface of the cooling pipes as it is heated by the latent heat released from the condensing vapor. Once the solution exits stage 1, it enters a brine heater, where its temperature is raised to the saturated temperature of water at the maximum operating pressure of the plant. The heated solution then re-enters stage 1. Its pressure is immediately reduced, causing a portion of the heated solution to flash into vapor. The vapor travels through a wire mesh, which removes any remaining salt, and condenses on the set of cooling pipes within that stage. This process is repeated until the solution reaches stage *n* (Tarifa and Scenna, 2001; Kalogirou, 2005; Khawaji *et al.*, 2008; Jones, 2013).

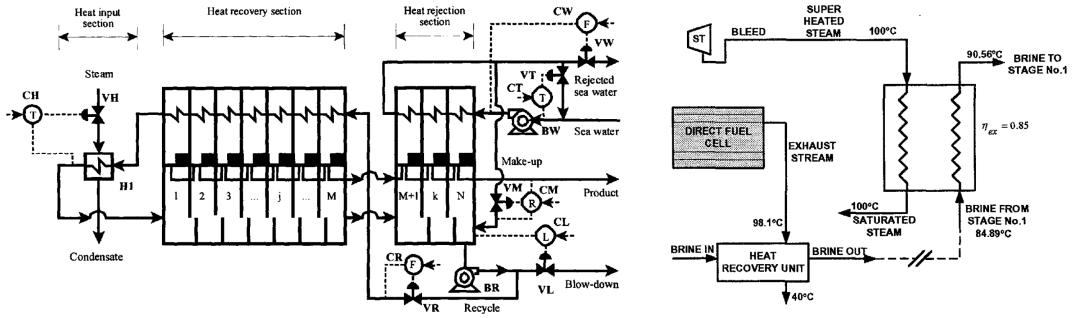

Figure 4. Multi-stage flash (MSF) process: (a) desalination system (reproduced by publishers permission, Tarifa and Scenna, 2001), and (b) integration with MCFC (reproduced by publishers permission, Al-Hallaj *et al.*, 2004).

MSF can work with a wide grade of energy source (25-100 °C). As shown in Fig. 4(b), it was revealed by Al-Hallaj *et al.* (2004) that such hybrid fuel cell/thermal desalination system is 5.6% more efficient than separate fuel cell thermal desalination system. In this case, the exhaust from the fuel cell replace some of the steam feed requirement from the gas turbine and therefore, is expected to increase power generation from the steam turbine while improving the overall efficiency of the fuel cell/MSF hybrid system.

1.3.3 Integration with membrane distillation (MD) desalination unit

Membrane distillation (MD) is a thermally-driven process, a low pressure, low temperature process, and operates at near atmospheric pressure (Khawaji *et al.*, 2008, Alkhudhiri *et al.*, 2012; Jones, 2013). It is a process in which an aqueous solution is heated and placed in direct contact with a microporous (about 10 nm to 1 μm), hydrophobic membrane. The membranes used are typically made of

polypropylene (PP), polyethylene (PE), polyvinylidene fluoride (PVDF), and polytetrafluoroethylene (PTFE) (Jones, 2013). The material properties of the membrane prevent liquid from entering the membrane pores, and thiscreates a liquid/vapor interface at the entrance of the membrane pores. The opposite side of the membrane (permeate collection side) is at a lower temperature. The temperature difference between the two surfaces of the membrane creates a vapor pressure drop within the membrane pores, which allows volatile materials in the feed to diffuse through the pores as the liquid feed comes into contact with the solid membrane. The volatile materials are collected on the cooler side of the membrane. As shown in Fig. 5, there are four types of MD systems: air gap membrane distillation (AGMD), direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD) and sweeping gas membrane distillation (SGMD).

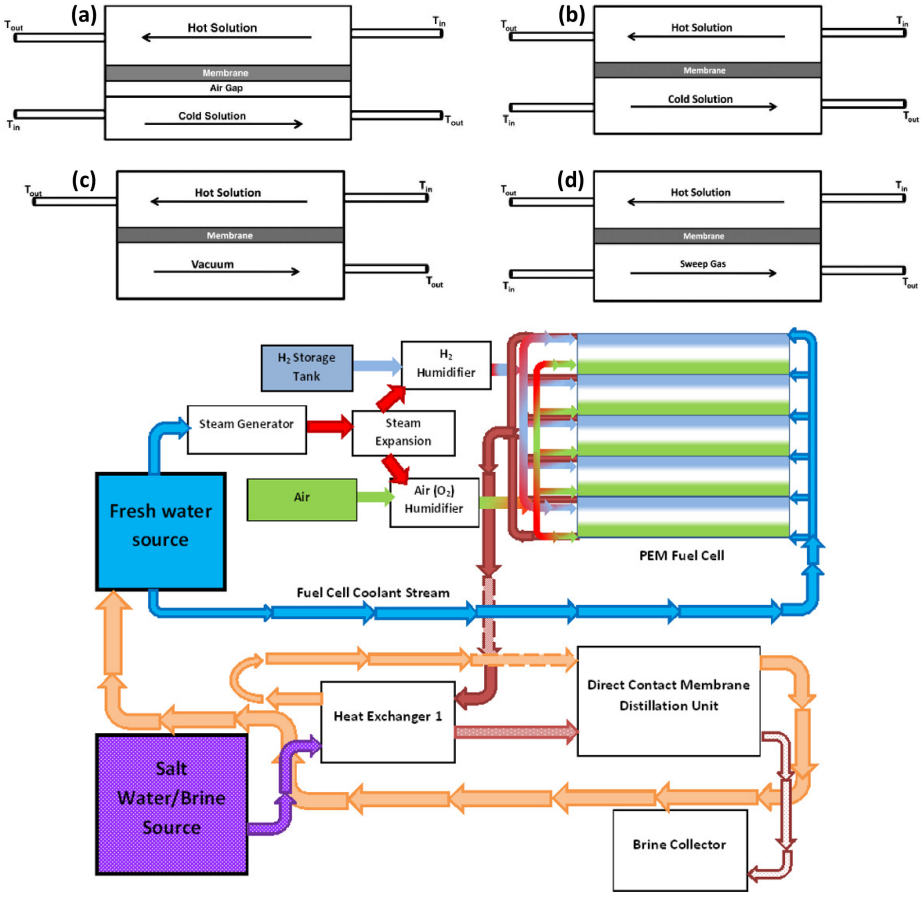

Figure 5. Membrane distillation (MD) systems: (I) (a) air gap membrane distillation (AGMD), (b) direct contact membrane distillation (DCMD), (c) vacuum membrane distillation (VMD) and sweeping gas membrane distillation (SGMD) (Alkhudhiri *et al.*, 2012), and (II) DCMD integration with PEM (Jones, 2013).

MD can work with a low grade energy source (20-85 °C). Figure 5(II) showns an example which consists of a high-temperature polymer electrolyte fuel cell (HT-PEMFC) coupled with DCMD

system. As revealed by Jones (2013), it is expected that the heat rejected by the PEM fuel cell will be sufficient for the amount of heat required for DCMD, as the temperature range for this process (20-80 °C) is within the range of operating temperatures for a Nafion® membrane PEM fuel cell. Additionally, Jones (2013) expected that the power produced by a combination of the PEM fuel cell and the steam turbine that is part of the steam generation system can have the capacity to provide all of the electrical power needed for steam generation, pumping, etc.

1.3.4 Integration with multi-effect distillation (MED) unit

It is known that the multi-effect distillation (MED) is the most efficient distillation process and reverse osmosis (RO) has the lower energy consumption (Bataineh, 2016). In MED thermal process (Fig. 6), the column pressures are adjusted such that the cooling (i.e. thermal energy removal) in one column functions as the heating source (thermal energy input) in another column (Al-Shammiri and Safar, 1999, Ghalavand *et al.*, 2015, Bataineh, 2016). In MED process, the sea water enters the first effect and is raised to the boiling point. Both the water feed and heating vapour to the evaporators flow in the same direction. The remaining water is pumped to the second effect, where it is once more applied to a tube bundle. This process continues for several effects, about 4 to 21 effects in a typical big plant. The increase in flashing stages can increase the internal energy recovery.

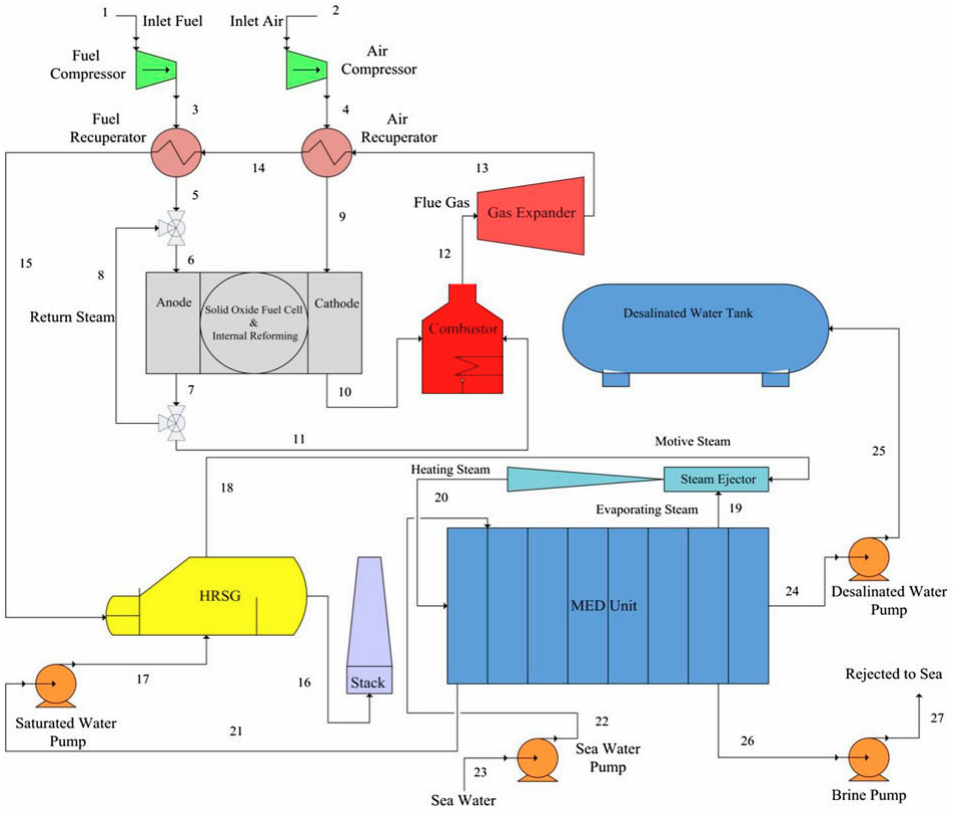

Figure 6. Integration of multi-effect distillation (MED) process with SOFC-GT (reproduced by publishers permission, Meratizaman *et al.*, 2016).

MED can work with a low grade energy source (70-80 °C) (Bataineh, 2016), and the thermal nature of MED process causes the integration of a desalination unit with a high-temperature power cycle like gas turbine (GT) in combination with the SOFC, with electrical efficiency of about 60% (Meratizaman *et al.*, 2014, Meratizaman *et al.*, 2016). The MED unit by Meratizaman *et al.* (2014) was presented as a solution for heat recovery in the 300-1000 kW range of (size of SOFC) SOFC-GT power cycle. The exhausted heat of SOFC-GT power cycle was used in heat recovery steam generator to produce a required motive steam for the desalination unit.

1.3.5 Integration with multi-effect boiling (MEB) desalination unit

As shown in Fig. 7, the conventional multi-effect desalting system (MEB) is the oldest method used to desalt seawater in large quantities (Darwish *et al.*, 2006). The MEB has the advantage of using a low-temperature heat source (steam or hot water) when it operates at low top brine temperature (TBT), and this can give much lower equivalent work or available consumed energy than MSF units. This system consumes about half the pumping energy of the MSF (Darwish *et al.*, 2006).

MEB can work with a low grade energy source (up to 70 °C). As discussed by Darwish *et al.* (2006) for MEB process, vapour is generated from hot water by flashing as it enters a flash chamber upstream the first effect. It is revealed that the hot water produced by the phosphoric acid fuel cells (PAFC) at 60-65 °C can be used as heat source to operate the MEB system.

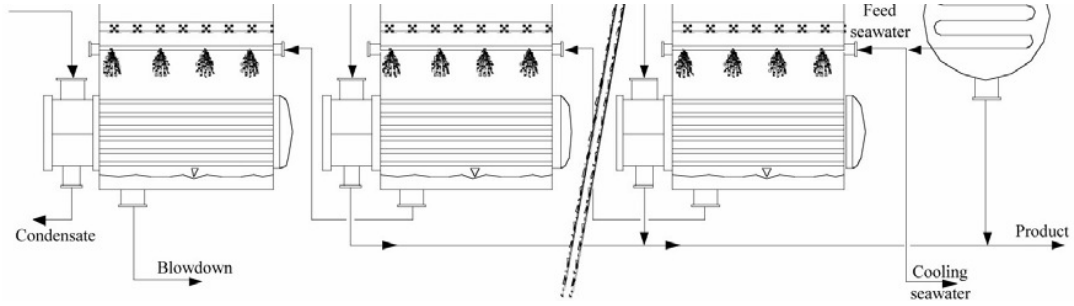

Figure 7. Multi-effect boiling (MEB) process: Backward feed multi-effect desalting system using horizontal tube evaporators (reproduced by publishers permission, Darwish *et al.*, 2006).

1.3.6 Integration with mechanical vapor compression (MVC) desalination unit

In the mechanical vapor compression (MVC) process, the heat for evaporating the sea water is generated through vapor compression (Ghalavand *et al.*, 2015). Two methods are used to condense the water vapor and to produce the amount of heat to evaporate the incoming sea water (e.g. mechanical compressor and a steam jet). In this method (e.g. Fig. 8), sea water held at 100 °C is evaporated and the vapor is passed through a compressor, which leads to an increase in vapor dew point, so vapor can be condensed by sea water indirect contact and cause to evaporate sea water.

MVC can work with a high grade energy source (up to 100 °C). The power consumption in MVC desalination method is high because of compressor usage (Ghalavand *et al.*, 2015), but it can become economically feasible when energised by fuel cell (e.g. phosphoric acid fuel cell (PAFC), which operate at higher temperatures than PEM fuel cells, as proposed by Kenet *et al.* (2003)). In MVC, the desalinated water vapor preferably passes through at least one compressor, which heats the water vapor, and then returns through the evaporator to heat brine in the evaporator. The evaporator of the desalinator may operate at approximately 40-45 °C while the

input brine is typically at 18-25 °C. Although PAFC fuel cells have been found to be less desirable than PEM fuel cells for many technologies due to their acid content and high temperatures (about 80-200 °C), Kenet *et al.* (2003) suggested that PAFC are preferred since the fuel cell is stationary and that waste heat is actually desired for heating the desalinator. However, Kenet *et al.* (2003) also suggested that PEM fuel cell, which also operates at elevated temperatures (about 80 °C) may be used.

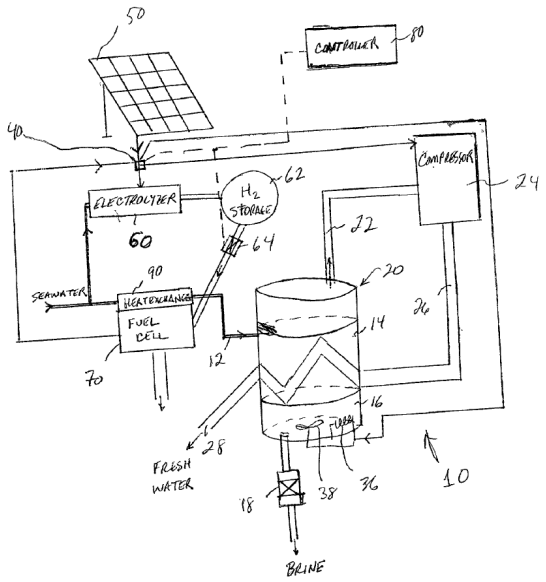

Figure 8. Mechanical vapor compression (MVC) process: Integration with phosphoric acid fuel cell (PAFC) (US 2002/0132097 A1, Kenet *et al.*, 2003). [Component details are as follows, 10: vapor compression desalinator, 12: water input line, 14: heat exchange section, 16: brine section, 18: valve, 20: evaporator, 22: vapor line, 24: compressor, 36: heater, 38: stirring device, 40: distributor, 50: renewable energy source, 60: electrolyzer, 62: hydrogen storage tank, 64: valve, 70: fuel cell, 80: controller, 90: heat exchanger]

1.3.6 Other examples of fuel cell integration with desalination unit

There are other examples of the integration of fuel cells (e.g. microbial fuel cell, MFC) with desalination units. As summarised by Gude *et al.* (2013), MFC operate in a galvanic mode where it employ microbial catalysts to extract oxidation current from waste organic matter in the anodic half-cell and use chemical catalysts in the cathodic half-cell to consume electrons in the presence of protons and terminal electron acceptor. In MFC, the anode is normally designed for treatment of municipal waste streams and high-strength organic wastes (e.g. cattle farms, breweries, landfills, chocolate factories, food processors) and the reducing conditions in the cathodic half-cell provide a legitimate route for treating oxidized contaminants (e.g. nitrates, chromium) in water bodies.

While integrating, Cao *et al.* (2009) modified MFC to develop a new water desalination method. The authors performed experiments with different concentrations of salt (up to 35g/L) and found that a single desalination cycle successfully removed approximately 90% of the salts from water. Chen *et al.* (2011) extended the work of Cao *et al.* (2009) using stacked MFC based desalination unit (i.e. microbial desalination cell, MDC), where they found that desalination cell number and external resistance have significant effect on total desalination rate. It is important to note that microbial desalination cell (MDC) is a variant of MFC which includes an additional

middle chamber for sustainable energy production (from organic wastes) and water desalination (Gude *et al.*, 2013). The MDCs can be designed for treatment of organic waste and simultaneous desalination of saltwater. Wen *et al.* (2012) used a biocathode in microbial desalination cell (MDC) to improve the cell performance for desalination and wastewater treatment. Meng *et al.* (2014) found that dewatered sludge as anodic substrate improves the stability of biocathode MDC for desalination purpose. Mohanakrishna *et al.* (2010) investigated an open air cathode MFC used for desalination and power generation purpose, whereas, Wang *et al.* (2012) investigated the performance of a MFC–membrane bioreactor integrated system for wastewater treatment. It was summarised that the low cost and efficiency of the integrated system demonstrated the prospect of using this technology for wastewater treatment in future. Ghasemi *et al.* (2013) performed an economical comparison study between sulfonated poly ether ether ketone (SPEEK) and Nafion 117 membrane used in MFC for wastewater treatment. It was suggested that the higher power density and low cost of SPEEK membrane for MFC demonstrated the potential for implementation at an industrial level.

Other rare examples of such integration include where Huicochea *et al.* (2011) tested a novel cogeneration system built-in to a water purification system. The system consists of a PEM fuel cell and an absorption heat transformer. They found that the cogeneration system offer an increase of efficiency by approximately 12.4% compared to a standalone fuel cell. Similarly, Klaysom *et al.* (2010, 2011) reported a new type of composite ion-exchange membrane for water purification application using electrodialysis desalination, where almost 50% reduction in power consumption was observed compared to pristine membrane.

1.4 ENERGY, ENVIRONMENTAL AND ECONOMIC FACTORS

It is known that carbon dioxide (CO_2) emissions are at an all-time high, with global estimates around 36 billion tonnes in 2013 (Olivier *et al.*, 2013). Hydrocarbon based energy consumption during desalination makes a significant contribution to total emissions. Since desalination has proven to be a reliable water supply source in many countries around the world, with the total global desalination capacity of ~60 million m^3/day in 2013 (Ziolkowska and Reuben, 2016). It is very important to explore in much detail the energy saving, environmental and economics effects of implementing any novel concept of integrated fuel cell/desalination systems. Such strategy can substantially reduce the cost of seawater desalination. This is possible as a new and environmentally friendly fuel cell technology with desalination in a dual purpose facility that simultaneously produces electricity and water. As summarised by Almarzooqi *et al.* (2014), desalination cost depends on many factors ranging from type of technology, energy cost, feed water salinity, capacity and many other site specific factors. Due to the large number of variables impacting the desalination cost it is usually difficult to give an absolutely fair comparison between the different technologies. The rationale for developing integrated energy-water systems is to reduce capital cost, energy consumption and the cost of desalinating seawater since 50–60% of a RO system operating cost is due to energy consumption (Singh, 2008).

As discussed by Khawaji *et al.* (2008), a cogeneration scheme is essential in conjunction with the power generation from an economic point of view. The global desalination industrial goal is to produce desalinated water at 50 US cents per m^3 of water and power at 2 US cents per kWh. For instance, the estimated water production cost for the seawater RO plant project with a capacity of 94,600 m^3/day in Tampa, USA was reported to be at \$0.55/m^3 (Wilf and Klinko, 2001). As seen above, many improvements have been made in fuel cell efficiencies in an effort to reduce harmful emissions and decrease cost of desalination operation. Further work is necessary to investigate the economic benefits and performance improvement and to quantify their economic benefits for specific markets and applications (Khawaji *et al.*, 2008).

1.5 CONCLUDING REMARKS

In recent years considerable progress in the knowledge concerning the inter-relationship of applied materials in fuel cells and resulting desalinated water quality could be made. Also a lot of different materials manufacturing methods have been developed and used to make fuel cell components and also entire cells. Only few have already proven their potential for a reliable and efficient production of relevant layers and components and promised the status for a technical breakthrough for mass production where a continuous operation with high throughput and yield producing the desired quality is required. However, obviously work related to mass production of integrated fuel cell/desalination system is lacking. A considerable investment of tens of millions of dollars is necessary for a serious market entrance and for entering the learning curve which would promise a breakthrough success and the required cost reductions. Considering the importance of and promising potentials for desalination in the future in many countries, long term multidisciplinary research programs are needed for the purpose of making the seawater desalination techniques integrated with fuel cell systems affordable worldwide.

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