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REVIEW ARTICLE

SEAWATER DESALINATION TECHNOLOGIES

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ABSTRACT

As the world population is growing, the need for fresh water is increasing. Water desalination is a mean for producing fresh water from saline water abundant in seas and oceans and recently attracted increased attention at various parts of the world. Various technologies have been used to desalinate saline water with different performance characteristics. This work reviews current desalination technologies and assess their performance in terms of input and output water quality, amount of energy required, environmental impact and cost. Comparative analysis was carried out based on these parameters and it was found that adsorption desalination is a promising technology that can handle feed water with high salinity (up to 67,000ppm) and produce potable water (10ppm) with minimum running cost (0.2$/m^3) and low environmental impact (0.6kg/m^3).

KEY WORDS: Seawater, Desalination, Thermal, Membrane, Chemical, Adsorption

1. INTRODUCTION

With the growing of world population, the need for fresh water is increasing. World water resources are mainly salty (97.5%) and fresh water (2.5%). Salty water is found in oceans, seas and some lakes while fresh water is either stored underground (30%) or in the form of ice / snow covering mountainous regions, Antarctic and Arctic (70%) but only 0.3% is accessible by humans (Bigas, 2013).With this limited amount of usable fresh water, desalination offers the means to meet the increasing demand for fresh water.

Desalination of salty water is the separation of dissolved salts to produce fresh water with an allowed level of dissolved solids. Desalination technologies are divided into three major groups, namely: (i) thermally-activated systems in which evaporation and condensation are the main processes used to separate salts from water, (ii) membrane-based systems where either pressure or electric field is applied on the salty water to force it through a membrane, leaving salts behind and (iii) chemically-activated desalination methods (Glueckauf, 1966; Frederick, 2010; Thu *et al*., 2013).

Thermally activated desalination systems include processes like: multi-stage flash (MSF), multiple-effect (MED), vapor compression distillation (MVC), humidification - dehumidification (HDH), solar (SD) and freezing (Frz) (Younos and Tulou, 2005; Reclamation and S.N. Laboratories, 2003). In these systems, heat energy is used either to boil or freeze the seawater or brackish water to convert it to vapor or ice so the salts are separated from the water. As a result, fresh water is obtained and salts remain as a waste (Reclamation and S.N. Laboratories, 2003). About 40% of the distilled water around the world is produced using one of these methods (Mabrouk, 2013). Membrane based systems use permeable membranes to create two zones where water can pass through leaving salt (Shatat *et al*., 2013; Greenlee *et al*., 2009).

The polymer materials of membranes are structured in a way such that they permit only the flow of fresh water and restrict the flow of large undesirable molecules such as salts (Greenlee *et al*., 2009; Khawaji *et al*., 2008). These membrane technologies consist of reverse osmosis (RO), forward osmosis (FO), electro-dyalysis (ED) and nanofiltration (NF) (Misdan *et al*., 2012). Chemically-activated desalination systems include ion-exchange, liquid–liquid extraction and gas hydrate or other precipitation schemes (Thu, 2010).

Recently, adsorption technology has been investigated for desalination application. In this technology an adsorbent material with high affinity to water like silica gel can be used to separate the water from the slats (Thu *et al*., 2013). Figure 1 shows flow chart of the various desalination technologies (El-Dessouky and Ettouney, 2002).The purpose of this work is to review the available desalination technologies and assess their performance in terms of operating parameters, energy required, cost, quality of produced fresh water, environmental impact and availability for commercial use.

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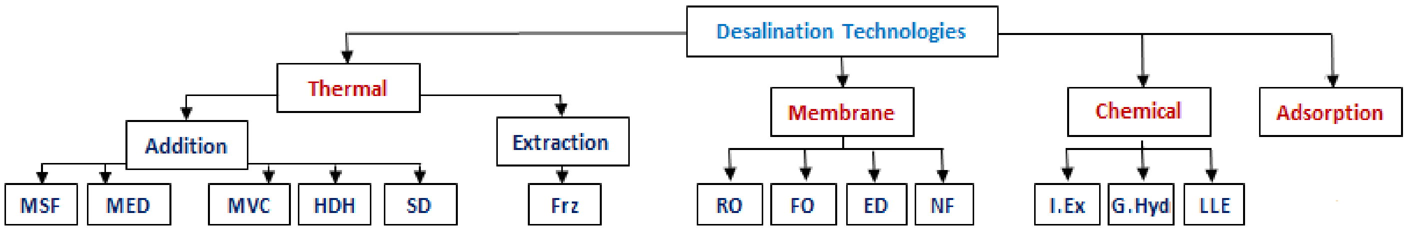

Figure 1. Classification of desalination technologies

2. Thermal desalination

Thermal desalination systems are the most widely used in the world. The principle of these systems depends on the difference between boiling or freezing temperature of water and salts. As a result, water will either be in the form of vapor, for heat addition processes (Pinder, 1968), or in form of ice, for heat extraction processes (Mandri *et al*., 2011), and consequently salt will be separated. These technologies are described below:

2.1. Heataddition processes

2.1.1. Multi stage flash (MSF)

MSF has been widely used for many decades and it is now one of the largest sectors in desalination applications (El-Dessouky and Ettouney, 2002). MSF systems consist of two main parts, heat addition section and heat recovery section as shown in Figure 2. The incoming seawater enters the condenser where it is preheated by the effect of latent heat of condensation of the distilled water while the flashed steam in the flash chamber is cooled down and condensed. After preheating the seawater in condenser, it is directed to the brine heater where a stream of hot steam enters to the heater and an exchange of heat occurs. As a result, steam condenses and seawater heats up more. After that, the heated unevaporated brine goes to the flash chamber where the pressure is lower than the atmospheric pressure so the seawater evaporates and this vapor is condensed in the condenser and collected in the distilled water storage tank. As seawater moves inside the flashing chamber and passes through several stages, the pressure decreases so the evaporation temperature decreases as well. The remaining salts from seawater evaporation are removed from the bottom of flashing chambers. In these systems there are about 15 to 40 stages of flashing to ensure minimum dissolved salts in the distilled water. Inside each stage there is a demister which prevents passage of water droplets carried by the upcoming vapor, otherwise, there will be salts inside the distilled water (Abduljawad *et al*., 2010; Baig *et al*., 2011).Usually this type of desalination plants is coupled with steam power plants to obtain low pressure steam for the process of seawater heating in the brine heater(Baig *et al*., 2011).MSF systems produce pure water with a low concentration of dissolved solids which reach about 10 ppm or less. In addition these systems are able to distill seawater with a high concentration up to 60,000 – 70,000 ppm (Cooley *et al*., 2006).

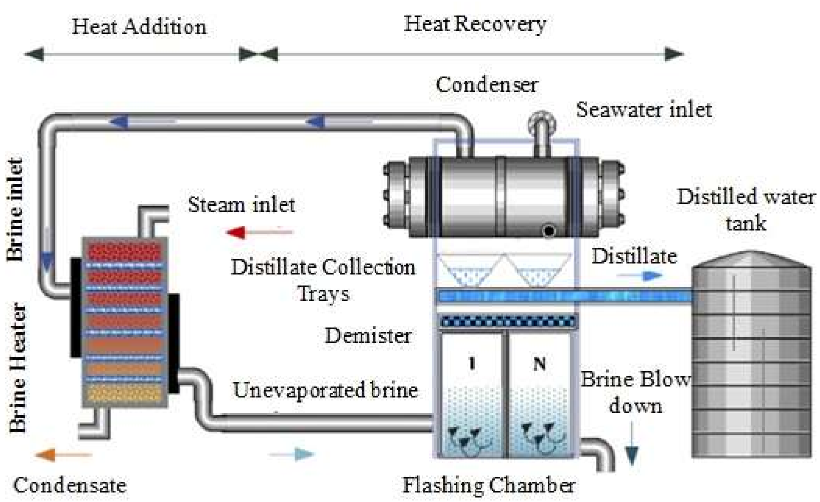

Figure 2. Schematic diagram for MSF system (Baig *et al*., 2011)

2.1.2. Multi effect desalination (MED)

MED is similar to the MSF technique in which seawater is evaporated and the highly concentrated water with salts is separated. The difference between these two techniques lies on the way of evaporation and heat transfer (Druetta *et al*., 2013). Figure 3 schematically shows, the MED system consisting mainly of a condenser, number of stages and flashing boxes. Firstly, intake seawater enters the condenser where it is being heated by the effect of latent heat of condensation of the vapor coming from the last stage.

As a result this vapor condenses and is added to the stream of distilled water while heated seawater exiting from the condenser is divided into two streams. The majority of seawater is returned back to the sea since it acted as a coolant and the rest is directed to be desalinated after being chemically treated and deaerated (Mohammad Ameri *et al*.,2009). These a water is sprayed a ten try to each stage to form a thin film that falls down onto horizontal tubes. In the first stage, heating of seawater is performed by external source of steam which flows inside these horizontal tubes.

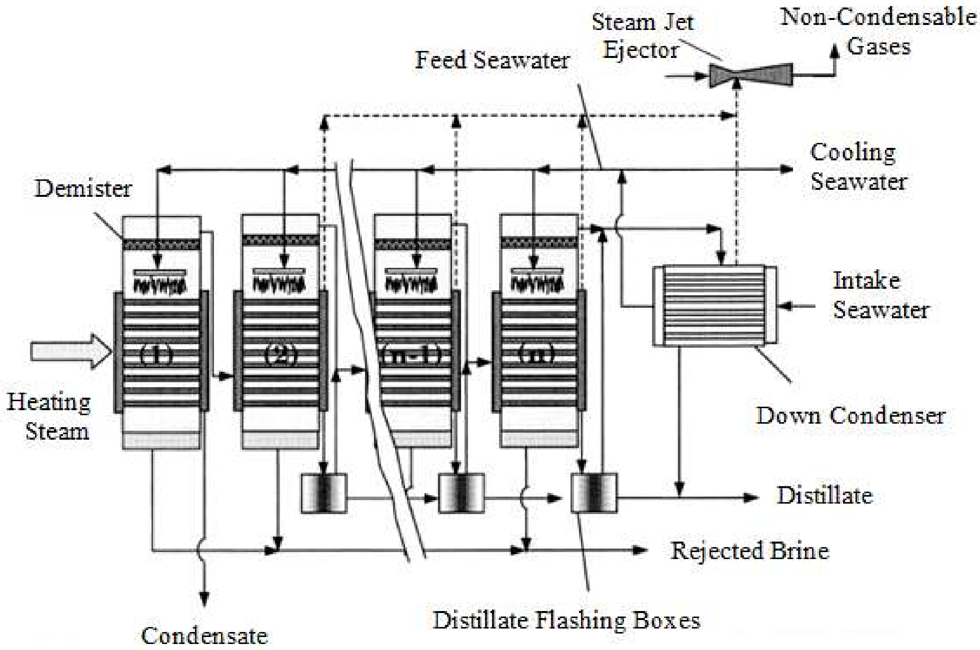

Figure 3. Schematic diagram for MED system (El-Dessouky *et al*., 2000)

This external source of steam is extracted either from power generation turbine, special boiler or flashed steam from waste energy source (Al-Shammeri and Safar, 1999). Because of heating, the seawater temperature is raised up to the boiling temperature correspondent to the pressure at the stage inlet before a small portion of water vapor is formed. As a result, evaporation occurs to the sprayed seawater and the vapor goes up through the demister.

The demister prevents the passage of brine droplets while the vapor is directed to the next stage. Passing through the demister helps in decreasing the saturation temperature of the vapor because of pressure drop that occurs in it. In the next stages, heating is performed through horizontal tubes by the vapor coming from the previous stages in addition to the flashed condensed distillate coming from the flash boxes. The use of flash boxes helps in the recovery of heat from condensed fresh water (El-Dessouky *et al*., 1998).The flow of the vapor inside the tubes is accompanied by further pressure drop which make some of this vapor condenses and this heat of condensation helps in the heating of the outside sprayed seawater.

By these successive stages, the pressure and temperature of evaporation decreases. The exiting vapor from the last stage and the flashed vapor from last flash box are directed to the condenser where they are condensed and distilled water is obtained. A vacuum pump is used to produce vacuum in the condenser to remove non-condensable gases from the cycle which may affect the heat transfer processes (Dessouky *et al*., 1998 and Druetta *et al*., 2012).

2.1.3. Mechanical vapor compression desalination (MVC)

MVC is one of the thermal desalination processes that rely on evaporation- condensation processes. The driving force of this system is a mechanical compressor driven by electric motor (Marcovecchio *et al*., 2010). The main components of such systems are heat exchangers that are used as pre-heaters for seawater, evaporator- condenser device, pumps and mechanical compressor. Part of seawater is firstly preheated by recovering the heat of the distilled water in the distillate feed preheater. The remaining sea water enters the brine feed pre-heater, in which it is heated and after that it mixes with water exiting from other pre-heater as shown in Figure 4.

The heated seawater is sprayed above horizontal tubes in the evaporator- condenser device. These tubes contain hot steam, so the seawater continues to be heated to the brine boiling temperature. The evaporated steam flows up through a demister that prevents droplets entrained within it to pass and then it is directed to the compressor. The output from the compressor is a high pressure and temperature steam that flows inside the horizontal tubes in the evaporator- condenser device. This steam is condensed and its latent heat is transferred to the sprayed seawater.

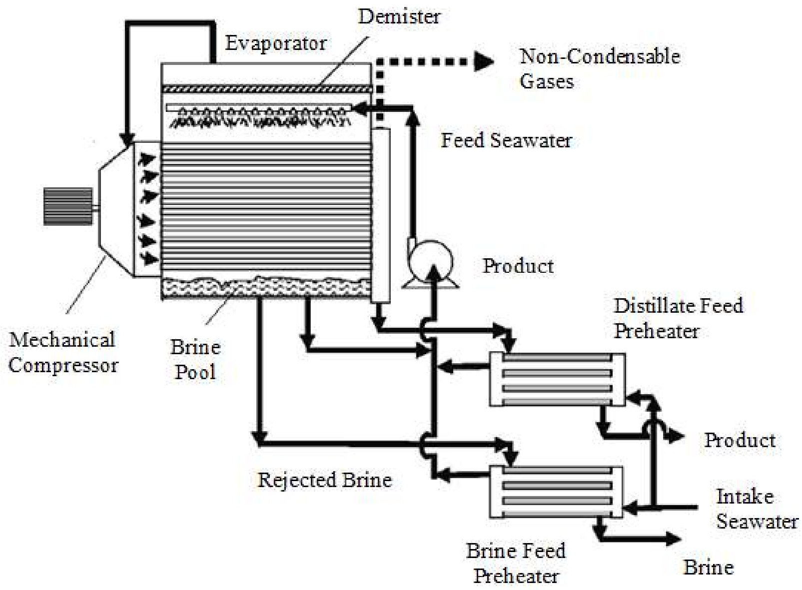

Figure 4. Schematic diagram for MVC system (Al-Sahali and Ettouney, 2007)

The condensed distillate water is collected from the side and then is directed to the pre-heater. The unevaporated brine is collected from the bottom of the evaporator to be used in the preheating of incoming seawater (Al-Sahali and Ettouney, 2007; Shen *et al*., 2014; Bahar *et al*., 2004; Aybar, 2002; Karameldin *et al*., 2002; El-Khatib *et al*., 2004). A vacuum pump is used to remove the non-condensable gases from the evaporator- condenser device (Veza, 1995).

2.1.4. Humidification- dehumidification desalination (HDH)

HDH process is similar to the rain cycle that occurs in nature. Saline water is evaporated then air carries this water vapor (humidification process) and then condenses (dehumidification process) so the distillate water is obtained (Miller and Lienhard 2013).The principle idea of these systems depends on the ability of dry air to carry amounts of water vapor and heat energy associated with its temperature. For example, 1 kg of dry air can carry 0.5 kg of water vapor and require about 2.8 MJ when its temperature increases from 30^{o}C to 80^{o}C (Bourouni *et al*., 2001).The main components of typical HDH system are humidifier, dehumidifier, heat source, water pumps and air blowers. There are different cycle configurations which are: closed air- open water (CAOW) water- heated systems, multi- effect closed air- open water (CAOW) water- heated systems, closed water- open air (CWOA) water heated system and closed air- open water (CAOW) air heated system (Kabeel *et al*., 2013; Narayan *et al*., 2010).

In closed air- open water (CAOW) water- heated systems as shown in Figure 5, the seawater is heated in the dehumidifier by the recovery of the latent heat of condensation of the water vapor entrained in the hot humid air stream. The seawater is further heated by an external heat source and then sprayed in the humidifier. The fine water droplets fall on a packing where heating and humidification processes occur to the counter flowing air through a direct contact process. After that, air is moved to the dehumidifier where distillate water is produced by condensation process (Thiel *et al*., 2013; Al-Hallaj *et al*., 1998).

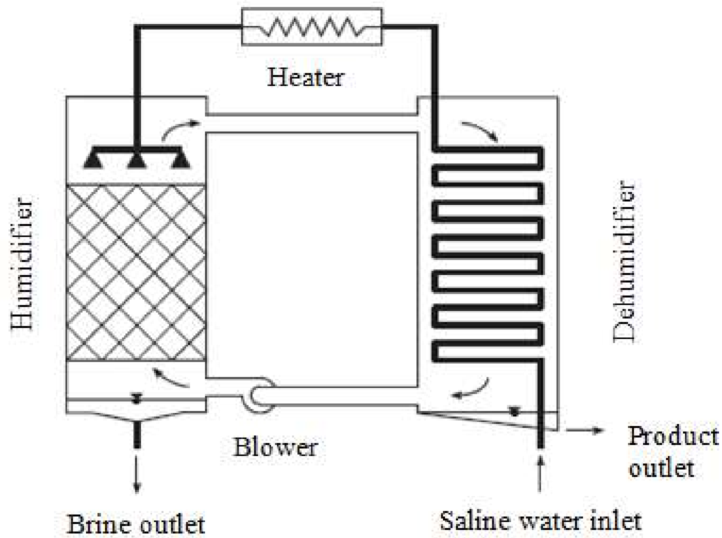

Figure 5. Schematic diagram for (CAOW) water- heated, HDH system (Thiel *et al*., 2013)

For enhancing the heat recovery in the dehumidifier, the multi- effect closed air- open water (CAOW) water- heated system is used as shown in Figure 6. In this system the only difference from that of the CAOW system is that the hot humid air in the humidifier is extracted to the dehumidifier at many points. This method helps to minimize temperature gaps between seawater in the dehumidifier and the humid flowing air (Narayan *et al*., 2010; Muller-Holst *et al*., 2007).

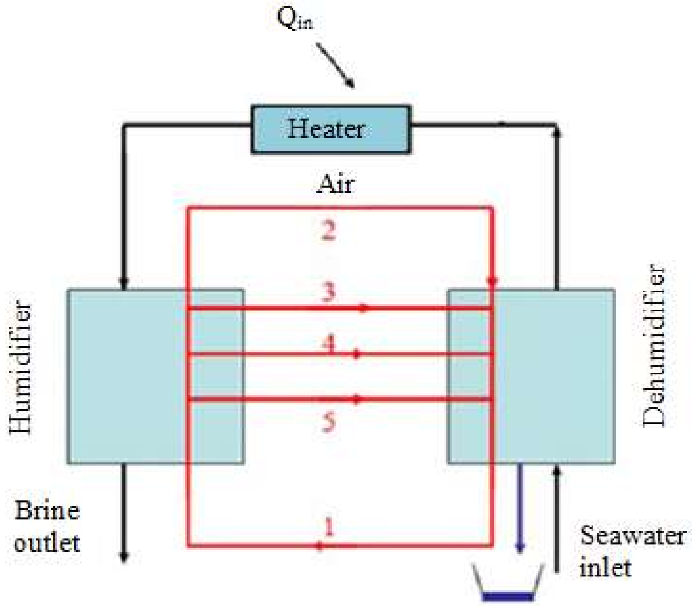

Figure 6. Schematic diagram for multi-effect (CAOW) water- heated, HDH system (Narayan *et al*., 2010)

For closed water- open air (CWOA) water heated system, Figure 7, the air enters the humidifier where it is being heated and humidified by the heated sprayed water coming from the heater. The air then enters the dehumidifier to heat up the incoming opposing seawater stream through indirect contact process. The air is discharged out of the system and fresh air is then extracted in the humidifier. As a result of dehumidification, condensed distilled water is extracted from the bottom of the dehumidifier. The seawater is heated and then goes for extra heating in the heater. The heated water then loses some of its energy as it partially evaporates and the remaining water is recirculated again to the dehumidifier. Here in this system, the thermal energy is utilized as the unevaporated hot water is recycled again (Narayan *et al*., 2010; Dai and Zhang, 2000; Dai *et al*., 2002).

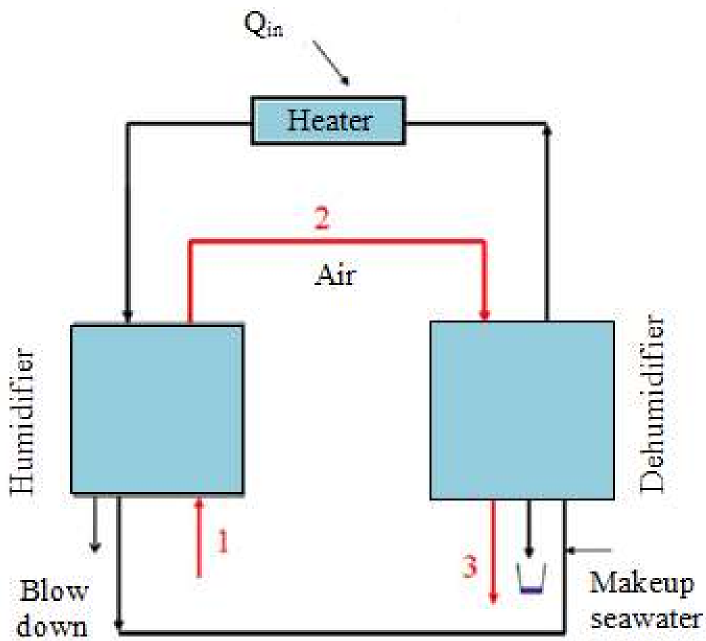

Figure 7. Schematic diagram for (CWOA) water- heated, HDH system (Narayan *et al*., 2010)

The last configuration of HDH is closed air- open water (CAOW) air heated systems. Such systems are either single or multi-stage with Figure 8 showing schematically a single stage configuration. Firstly air is heated to a temperature around 80- 90^{o}C in the heater then goes to the humidifier where it becomes cool and saturated because of sprayed seawater.

Then air is directed to the dehumidifier where water vapor is condensed to produce distilled water while heating the seawater. The exit air is recirculated again to the humidifier through the air heater. For the seawater, it has the same flow path as the first two configurations. The problem in the single stage is that the air humidity can only reach 6% by weight which is very low (Narayan *et al*., 2010) so multi-stage systems solve this problem by further heating and humidification of air through several stages.In the multi-stage type, air humidity increases up to 15% by weight (Yamalı and Solmus, 2008; Chafik, 2003; Chafik, 2004; Ben Amara *et al*., 2004; Houcine *et al*., 2006).

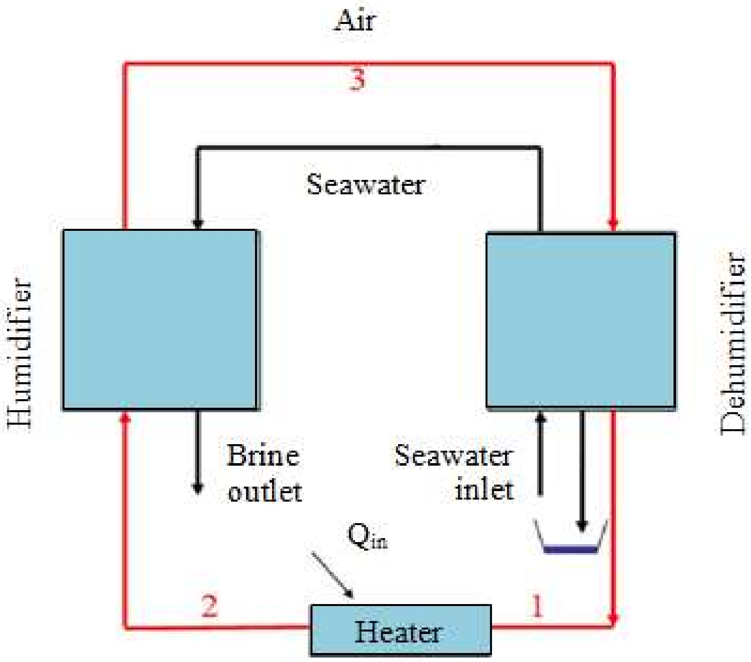

Figure 8. Schematic diagram for (CAOW) air- heated HDH system (Narayan *et al*., 2010)

2.1.5. Solar desalination (SD)

SD systems utilize the free energy of the sun to distill water and are classified in two categories, separated or integrated. Separated systems, or indirect systems, are those who use solar energy only for heating seawater or for generating steam for conventional water desalination plants like MSF, MED or RO. In integrated systems, or direct systems, solar collectors and condensers are integrated with each other (Garcia-Rodriguez *et al*., 2002; Garcia-Rodriguez and Gomez-Camacho, 2001; Lindblom, 2010; Garcia-Rodriguez, 2002).This section will deal only with direct systems as indirect ones were covered earlier in this paper. Direct systems are suitable only for low production requirements typically up to 200m^3/day as the operating temperature and pressure are low. The basic solar still, Figure 9, consists of a basin covered with tilted glass allowing air to be in between. The basin is filled with seawater which evaporates when receiving solar rays. As the water vapor is produced it mixes with air and goes up until it touch the cooler glass cover then it condenses.

The condensed distilled water moves along the tilted surface by gravitational force to be collected from the sides of the basin and the unevaporated brine is drained from the bottom of the basin (Fath, 1998).As this system design suffers from low efficiency, 30-40% (Mink *et al*., 1998),development techniques could be made (Qiblawey and Banat, 2008) as single slope or double slope basin still (Tiwari *et al*., 1986), still with cover cooling (Haddad *et al*., 2000),still with additional condenser or still with black die (Fath,1998).Other modifications are wick still (Sodha *et al*., 1981), diffusion still (Grater *et al*., 2001), solar still greenhouse combination (Chaibi, 2000; Davies and Paton, 2005) or multiple-effect basin stills (Schwarzer, 2001).

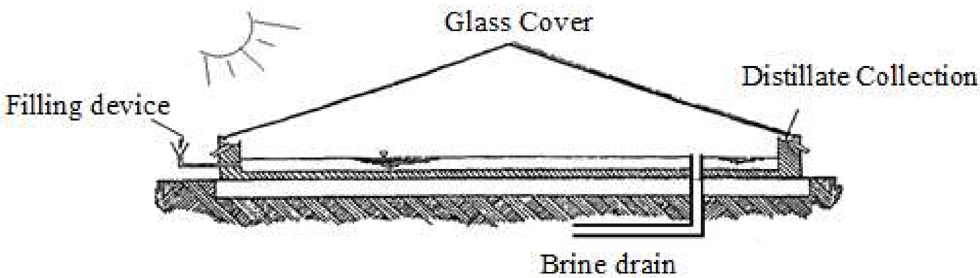

Figure 9. Schematic diagram for Simple basin solar still (Fath, 1998)

2.2. Heat extraction processes

2.2.1. Freezing desalination

The main reason of using freezing desalination processes is its reduced cost compared to other heat addition desalination processes since the latent heat of fusion of ice is only one seventh that of evaporation of water (Mtombeni *et al*., 2013; Shonet, 1987). Also the heat addition in freezing cycles is not considered as energy input to the system as compressor work is the only input energy. Freezing systems have two major divisions, direct and indirect contact depending on the cooling system itself. Direct contact systems uses the flow of refrigerant itself in contact with seawater to cool it down but for indirect contact systems, a heat exchange surface is used to separate between refrigerant and seawater while permitting heat transfer between them (Rich *et al*., 2012).The first type of direct contact systems is called "vacuum freezing vapor compression" (VFVC) shown in Figure 10. In this system the refrigerant could be the seawater itself and by applying a very low pressure on the seawater, it flashes and vaporizes absorbing heat from the seawater and the produced ice is removed from the remaining brine then washed. For melting the ice, the produced water vapor is compressed and is used to melt the ice for the production of distilled water (McCormack and Andersen, 1995).

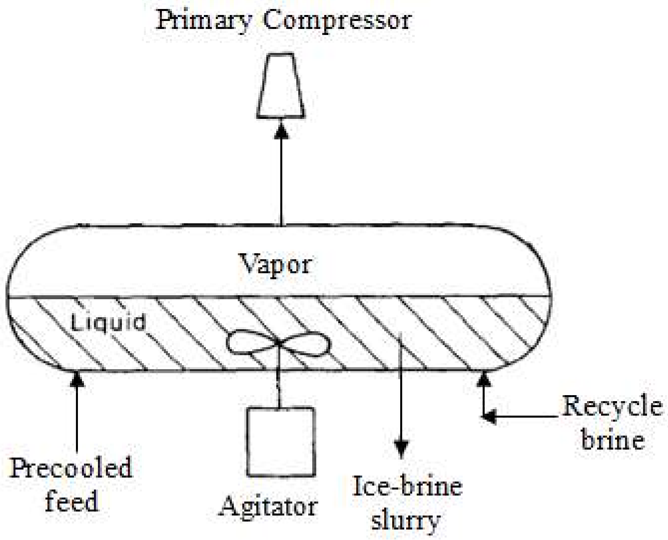

Figure 10. Schematic diagram for Vacuum Freezing Vapor compression system (Hahn, 1986)

The second type in the direct contact systems is called "secondary refrigerant freeze" (SRF). Here another refrigerant other than seawater is used but have to be more volatile and less soluble in water. The refrigerant is compressed and cooled to temperature lower than the freezing point of seawater then injected through nozzles in the water. The refrigerant evaporates and water starts to crystallize then these crystals flow up the water surface, due to buoyancy forces, where it is collected and the refrigerant vapor is collected from the top of the system and then compressed as shown in Figure 11. The collected ice is washed and then melted by the compressed refrigerant to obtain the distilled water (Rahman *et al*., 2006; Rice and Chau, 1997).

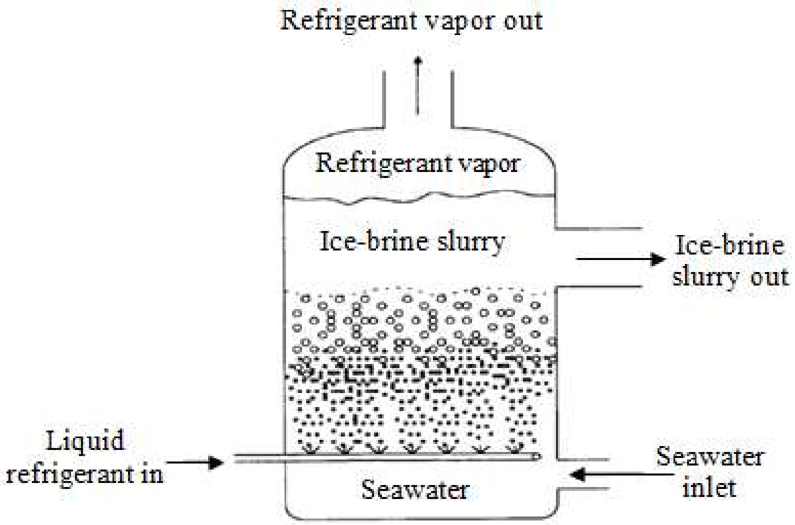

Figure 11. Schematic diagram for SRF process freezer (Rice and Chau, 1997)

The second division of freezing systems is indirect contact systems. As shown in Figure 12, incoming seawater enters a heat exchanger to cool down then is pumped to the freezer where it cools till ice crystals are formed. A washer column is then used to separate the ice crystals and the brine. The ice is moved to the melter where it is converted to fresh distilled water by utilizing the heat of condensation of the compressed refrigerant. The fresh water is firstly used as a cooling fluid for the incoming seawater then it is collected outside the system. Also the separated brine in the washer is directed to the heat exchanger to cool down the seawater. Small part of the fresh water after formation in the melter is used in the washer for the separation of ice and brine processes (Lu and Xu, 2010).

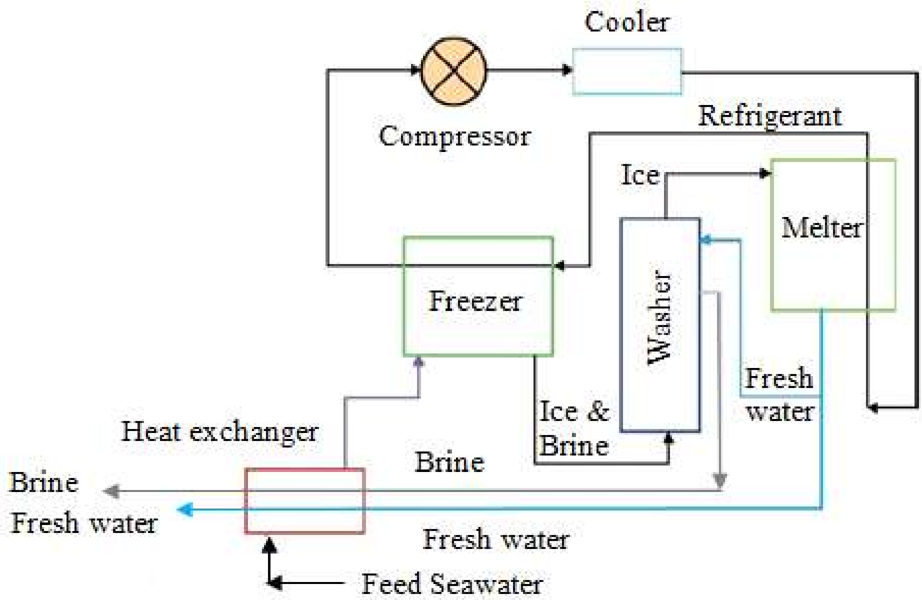

Figure 12 Schematic diagram for Indirect Contact freezer (Lu and Xu, 2010)

3. Membrane based desalination

Membrane based desalination processes do not depend on phase change of seawater like thermal systems but they depend on the separation of salts from seawater either by pressure difference between two sides of a membrane or by electric charge difference between two membranes (Guyer, 2013). The types are as follows:

3.1. Reverse osmosis (RO)

Osmosis process is a natural phenomenon in which the water flows from the lower concentration side to the higher concentration side through a semi-permeable membrane. This flow stops when chemical potential equilibrium occurs and at this stage there is a pressure difference between the two membrane sides equal to the osmotic pressure of the solution as shown in Figure 13 (a).For desalination application, it is needed to perform the reverse of this natural process which is moving the water from the highly concentrated side to the lower concentration side leaving salts in the first side. This is the reverse osmosis process where a pressure higher than the osmotic pressure is applied on the higher concentration side to let pure water only pass through the membrane, Figure 13 (b) (Greenlee *et al*., 2009; Fritzmann *et al*., 2007; Williams, 2003; Ratnayaka *et al*., 2009).

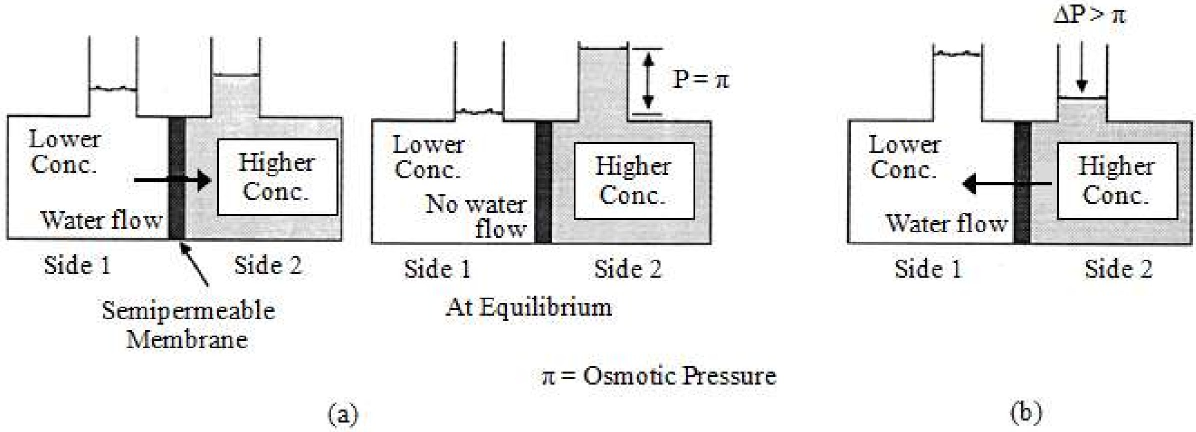

Figure 13. Schematic diagram for, (a) Osmosis process, (b) Reverse Osmosis process, (Williams, 2003)

The reverse osmosis plant originally consists of four main components: pretreatment device, high pressure pumping system, membrane separation system and pretreatment for produced water, Figure 14. Firstly, the incoming seawater is pretreated to be suitable for salts separation in membranes. In pretreatment section, suspended solids are removed, ph of seawater is adjusted and threshold inhibitor chemical materials are added to control scaling caused by calcium sulphate. Secondly, the pretreated seawater is pumped to high pressure, about 800-1000 Psi, according to the membrane and the salinity of the water. Thirdly, the high pressure water enters the separation system where the membranes prevent the passage of salts and only fresh water is permitted to pass. Some salts pass with the fresh water, depending on membrane material and efficiency, so post treatment is required. Finally the produced water is post treated as ph is adjusted to reach value of 7 and degasified to become suitable for human use. For recovering part of the energy used in pumping systems, the high pressure rejected brine is used to rotate a turbine to generate electricity to drive the pumping system (Meganck *et al.*,1997; Raluy *et al.*, 2006; Khawaji *et al.*, 2007).

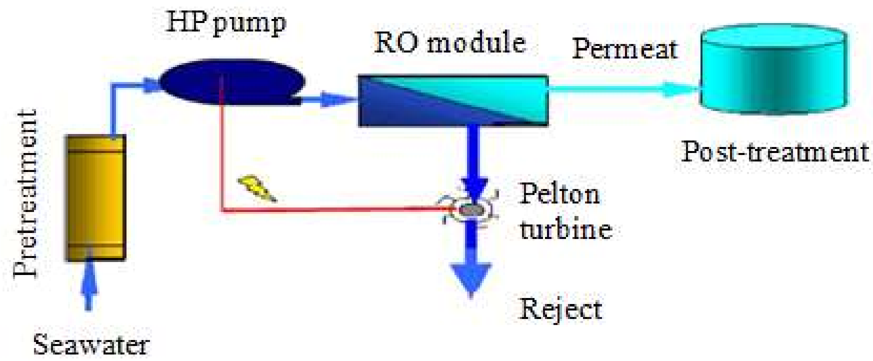

Figure 14. Schematic diagram for Reverse Osmosis Plant (Raluy *et al.*, 2006)

3.2. Forward osmosis (FO)

Due to the high energy required in the pumping processes, another alternative technique is used which is forward osmosis (FO). In this system the same principle of osmotic phenomenon is applied except that the driving force results from the concentration difference between the two sides of the membrane. One side contains saline seawater and the other contains highly concentrated draw solution (ammonia- carbon dioxide). As shown in Figure 15, fresh water passes through the membrane towards the ammonia-carbon dioxide solution. After that thermal energy is used to separate the fresh water from the draw solution at the draw solute recovery system (Chanukya *et al.*,2013; McCutcheon *et al.*, 2005; McCutcheon *et al.*, 2006; Tang and Ng, 2008; Phuntsho et a., 2014; Danasamy, 2009).

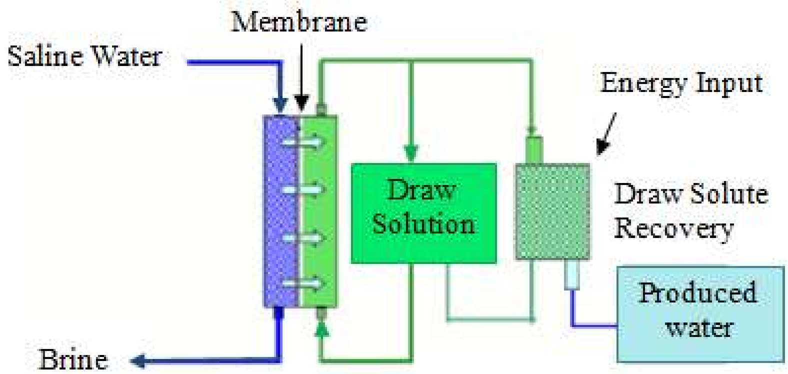

Figure 15. Schematic diagram for Forward Osmosis Plant (Danasamy, 2009)

3.3. Electro-dyalisis (ED)

The principle of operation of ED systems is the use of electric energy to separate salts from brackish water through membranes. An electric field is applied on a positive electrode, anode, and negative electrode, cathode. Between electrodes, there are many anion and cation exchange membranes, AEM and CEM respectively, which separate salt ions in the brackish water. Because of different charges, positive cations in brackish water migrate towards negative electrode through cation-exchange membranes and negative anions migrate towards positive electrode through anion exchange membranes, Figure 16. In these systems there are two parallel streams along each side of each membrane, high concentrated saline water and diluted water. These membranes are stacked together and fixed with plastic spacers.

Every 20 minutes of operation, a process called electro-dyalisis reversal (EDR) is performed. In EDR, an inverter is used to reverse the polarity of electric field to prevent scale formation (Tsiakis and Papageorgiou, 2005; Charcosset, 2009; AlMadani, 2003; Ortiz *et al*., 2006; Ortiz *et al*., 2007; Valero *et al*., 2011).

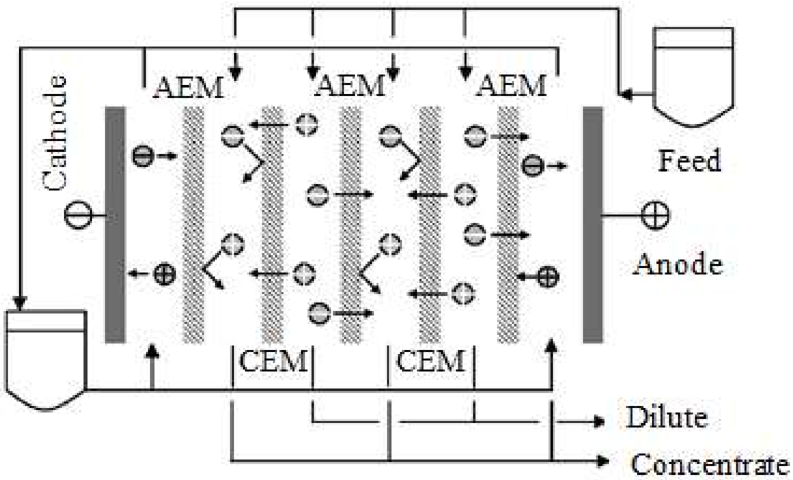

Figure 16. Schematic diagram for Electro-Dyalisis process (Charcosset, 2009)Error! Reference source not found.

3.4. Nanofiltration (NF)

As reverse osmosis process, nanofiltration is also a pressure driven desalination process. In NF systems there are semi-permeable membranes that prevent the flow of salts across them. The main difference between NF and RO is the selectivity of dissolved material that can be removed. NF is capable of preventing multivalent ions such as calcium and sulphate, (typically 80- 85%), while has less capability for monovalent ions as sodium and chloride, (typically 10- 40% according to membrane material and operating condition). NF is suitable for the separation of particle sizes in the range 0.01 to 0.001micrometer (Hassan *et al*., 1998). Nowadays, NF is emerging as an alternative technology to other membrane systems due to its higher energy efficiency, about 20% electric energy saving, ability to work with lower pressures, 6 to 14 bars, and applicability for higher permeate flow (Ratnayaka *et al*., 2009; Hassan *et al*., 1998; Subramanian and Seeram, 2013; Haddada *et al*., 2004; Abid *et al*., 2011; Al-Shammiri *et al*., 2004; Ahmad *et al*., 2004).

As conventional NF systems are used for low salt water (brackish water), some modifications to this system were performed to meet different demands as dual-stage nanofiltration for applications of seawater desalination. In dual-stage NF, seawater is pumped to the first stage using high pressure pump where a high performance NF membranes reject some of the salts in seawater and produce water with a TDS equivalent to brackish water. Then, in second stage, other high performance NF membranes get the produced water after pumping again to produce potable water as shown in Figure 17 (AlTaee and Sharif, 2011; Liu *et al*., 2013; Catherine *et al*., 2007). For the system to handle seawater for potable water production, brine produced from second stage has to be recycled back to the first stage (Vuong, 2006).

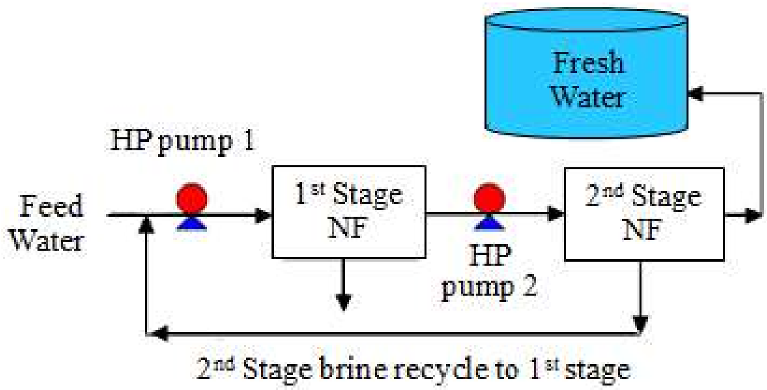

Figure 17. Schematic diagram for Dual-Stage NF Plant (AlTaee, 2011)

4. Chemical desalination

Unlike other desalination techniques, chemical desalination systems depend on chemical differences rather than pressure differences or phase change (Gibbs).

4.1. Ion exchange

Ion exchange is an analytical chemical separation technique where different ionic materials are allowed to be selectively retained on an ion exchange resin. These resins consist of large amounts of firmly attached bonds on their surfaces. They can absorb one type of ions reversibly. Resins are like small spheres with diameters in the range of 0.4 to 0.8 micro meters. Positive charged ions are captured by cation exchange resin, while anion exchange resin capture negatively charged ions **(**Greiter *et al*., 2002**)**. In an ion-exchange unit as shown in Figure 18, water enters a tank containing high capacity exchange beads (cation exchange resin). These beads are saturated with either sodium or potassium which are known as replacement ions. While water passes through this tank, an exchange occurs between contaminant ions and replacement ions which are released to the water. A regeneration process is needed to recover replacement ions which were released into the water.

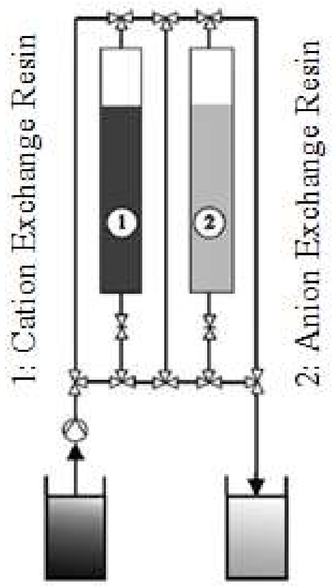

Figure 18. Schematic diagram for Ion-Exchange process (Greiter *et al*., 2002)

A salt brine solution is used to flush the ion exchange resin for the regeneration process. For removal of negative ions such as nitrate, arsenic and bicarbonate, anion exchange resin is used. In this resin, breads are saturated with negatively charged ions such as chloride and hydroxide. This type of desalination was found to be suitable for water treatment and for brackish water desalination **(**Amirault *et al*., 2003; Weiss, 1966; Egozy *et al*., 1980; Harland, 1994; DeSilva, 1999; Michaud, 2011**)**.

4.2. Gas hydrate

Gas hydrates, or clathrate hydrates, are crystalline solid structures that consist of water and small molecules such as CO_2, N_2, CH_4, H_2 and others which are formed under low temperature and high pressures. In other words, if small hydrocarbon molecules or non-hydrocarbon compounds are in gas or liquid phase and at high pressure was cooled to temperature near 0^oC, then solid crystals like snow may form. These solid water crystals act as host molecules that form cage structure which contains guest compounds entrapped inside. This is called gas hydrate. Desalination processes are based on phase change from liquid to solid then physical processes are required to separate solids from the remaining liquid phase.

As shown in Figure 19, seawater is pumped then cooled in the first heat exchanger by the counter current flow of brine and potable water streams. Then, a reactor is used to form slurry containing hydrate crystals which are filtered and washed in the separator that results in two streams; brine and washed hydrate crystals. This brine exchanges heat with seawater and the excess hydrate former (i.e. refrigerant) in first and second heat exchangers, respectively then discharged. Washed hydrate crystals are pumped to a decomposer which produces potable water and hydrate former. Potable water exchanges heat in the first and second heat exchangers then is collected out of the system.

The hydrate former goes to a throttling valve then to the reactor. In the reactor, hydrate crystals are formed as heat is removed from it by vaporization of liquid hydrate former which then takes part in hydrate structure. A compressor compresses the excess hydrate former which is then directed to the decomposer for destroying hydrate crystals and cooling. Finally, this hydrate former is further cooled in the third and second heat exchangers and then throttled in the throttling valve (Eslamimanesh *et al*., 2012; Javanmardi Moshfeghian and 2003; Park *et al*., 2011; Lee *et al*., 2011; Qi *et al*., 2012; Bradshaw *et al*., 2008; Max and Pellenbarg, 2000; McCormack and Calif, 1996; McCormack and Niblock, 1998; Aliev *et al*., 2008). Gas hydrate used for seawater desalination is considered a developing technology and more research is required (Corak *et al*., 2011).

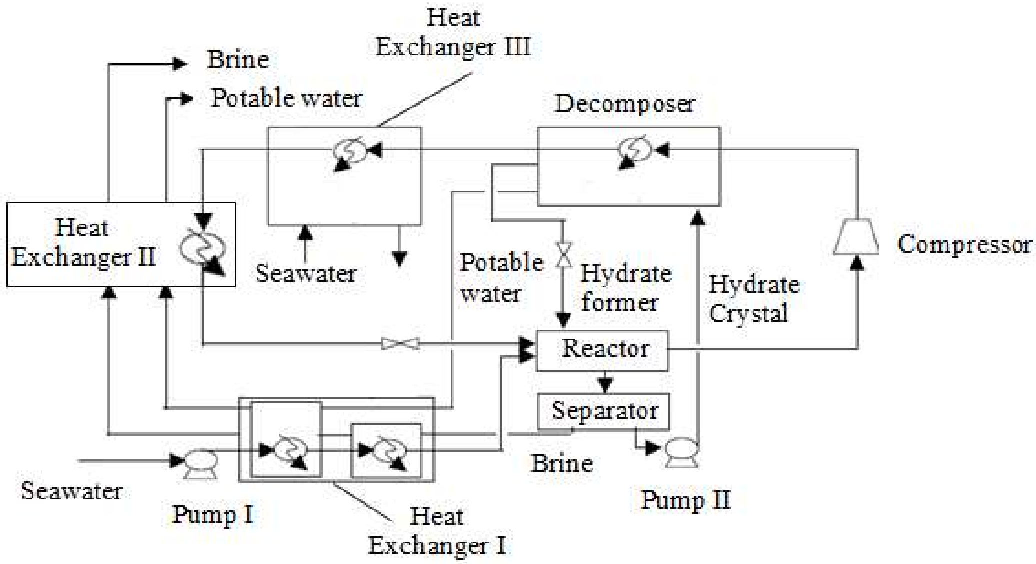

Figure 19. Flow sheet for seawater gas hydrate desalination process (Javanmardi and Moshfeghian, 2003)

4.3. Liquid-liquid extraction

In this system, a specially tailored polymer solvent is used to extract fresh water in a desalination process at temperatures not more than 60^{o}C. When seawater is contacted with these polymer solvents, two phases are produced; a polymer phase containing dissolved water and an aqueous phase in which the polymer is insoluble. As shown in Figure 20, seawater is mixed with a polymer solvent thereby forming aqueous two phase systems the first is polymer rich extract phase and the other is polymer lean phase. Change in temperatures is applied to recover the polymer without water evaporation. This is done as the polymer solvent is miscible in water at lower temperatures and with slight increase in temperature; it becomes immiscible in water so water can be extracted. The main solvents applicable are amines and polymers but there are no such commercial plants available (Polykarpou and Dua, 2013; Miller, 2003; Milosevic *et al*., 2013; Kimberlin *et al*., 1965; Lazare, 1982; Lazare, 1992; Polykarpou and Dua, 2012).

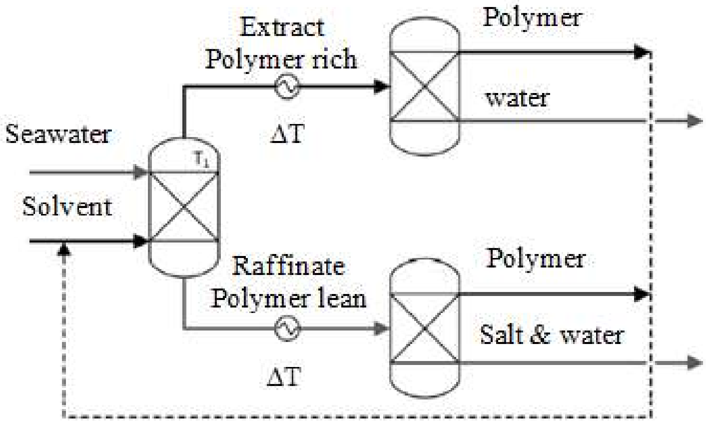

Figure 20. Schematic diagram for Liquid-Liquid Extraction process (Milosevic *et al*., 2013)

5. Adsorption desalination

The working principle of this process is the ability of porous adsorbent material to adsorb water on its surface. The high vapor affinity of an unsaturated adsorbent allows the water vapor adsorption on it within one half cycle period, while this adsorbent could be regenerated in the next half cycle by heating it at low temperatures. These low temperature heat sources are typically in the range of 50 to 85^{o}C depending on the type of the adsorbent. The adsorbents used are made of hydrophilic and highly porous materials that have huge surface areas in the range of 500 to 800 $m^{2}g^{-1}$.Silica-gel adsorbent is the most commonly used in the desalination processes.

The basic components in an adsorption desalination plant, Figure 21, are adsorption bed, evaporator and condenser. Firstly, seawater is charged in the evaporator where it evaporates at low temperature and pressure. As valve 1 is opened, water vapor is adsorbed by the adsorbent in bed 1. This adsorption process is exothermic, so cooling water is required to remove this heat.

After bed 1 becomes saturated, valve 1 is closed and valve 2 is opened. Hot water is now supplied in the heating coil inside the bed to the desorption process for the adsorbent regeneration. The produced water vapor exiting from the bed is condensed in the condenser using a cooling coil where it is condensed and collected as potable water.

When all of the water vapor is regenerated, valve 2 is closed and the cycle is repeated. For bed 2, the same processes occur but alternating with bed 1 (Thu, 2010; Towler and Sinnott, 2013; Thu *et al*., 2013; Ng *et al*., 2013; Wu *et al*., 2011; Wu *et al*., 2012; Wu *et al*., 2010; Ng *et al*., 2012; Sharafian and Bahrami, 2014; Chakraborty *et al*., 2011; Gupta and Ali, 2013).

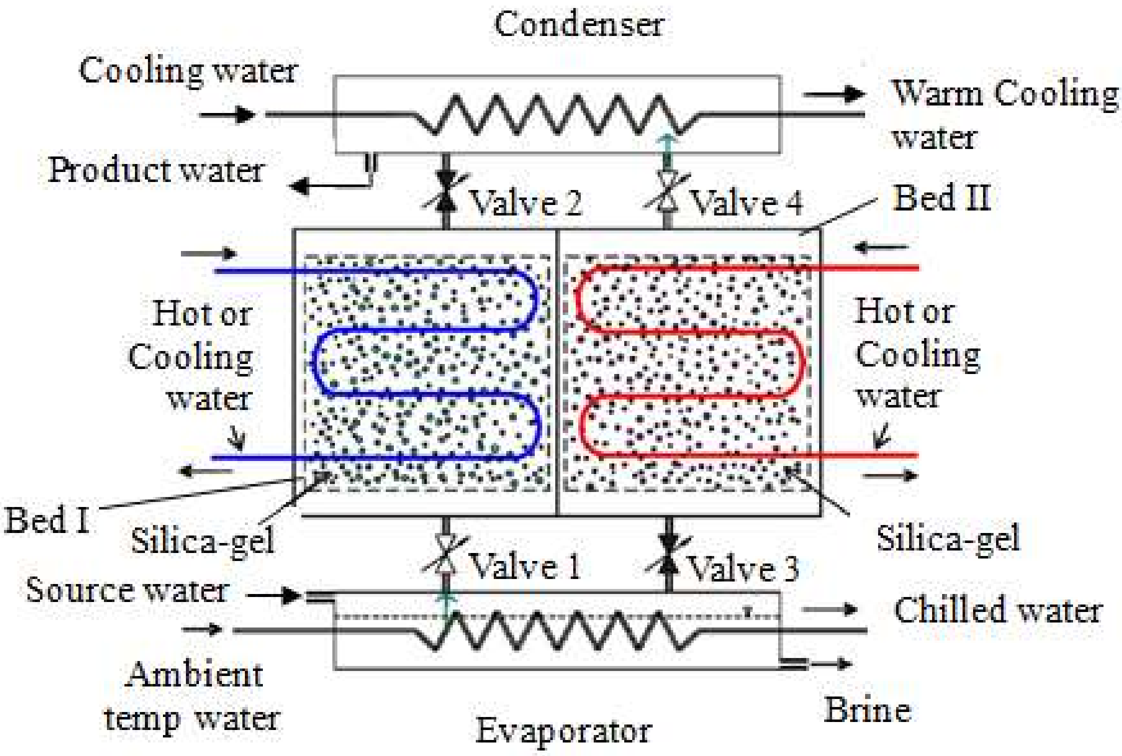

Figure 21. Schematic diagram for a 2 Bed Adsorption Desalination Process (Ng *et al*., 2013)

For getting higher cycle efficiencies, there are many modifications to this basic cycle which include; four adsorption beds instead of two, evaporator- condenser heat recovery circuit and internal condenser-evaporator heat recovery device (Thu, 2013; Wang and Ng, 2005; Thu *et al*., 2011). Adsorption desalination systems have the advantages of no moving parts except for pumps and valves. Also they are capable of desalinating both brackish and seawater even if organic compounds exist.

Moreover, they can be driven with low grade waste heat which minimizes global warming and CO_2 emissions instead of being discharged into the environment. Working at low temperatures minimizes the chances of fouling and corrosion inside the evaporator. Finally, these systems can also produce cooling effect beside desalination which is important in the hot regions with limited supply of fresh water (Thu *et al*., 2009; Wu *et al*., 2012).

6. DISCUSSION

There are a number of parameters that influence the performance of desalination technologies, these are: quality of salty water to be desalinated, required salinity level of produced potable water, capital and running costs for the selected technology, type of available input energy, required amount of produced potable water, environmental impact of the technology and available site properties **(**Gastli *et al*., 2010; Borsani and Rebagliati, 2005; Goswami and Stefanakos, 2013**)**. In this section, comparative assessment of these parameters for the various technologies described above will be presented.

6.1. Brackish or seawater salinity

According to salinity level, water is categorized into brackish or seawater. Brackish water contains total dissolved solids TDS higher than potable water and lower than seawater. Potable water should have TDS lower than 1000 ppm (or mg/l) and brackish water in the range of 1,000 to 25,000 ppm while seawater has an average of 35,000 ppm TDS concentration **(**Thu *et al*., 2013; Reclamation and S.N. Laboratories, 2003; W.H. Organization, 2008; Kalogirou, 2014**)**.

Figure 22 compares the feed water maximum salinity level that can be processed by each technology. It is clear that most of the technologies can handle a TDS value of less than 45,000ppm while the MSF and Ads technologies can handle higher values of TDS close to 70,000ppm.

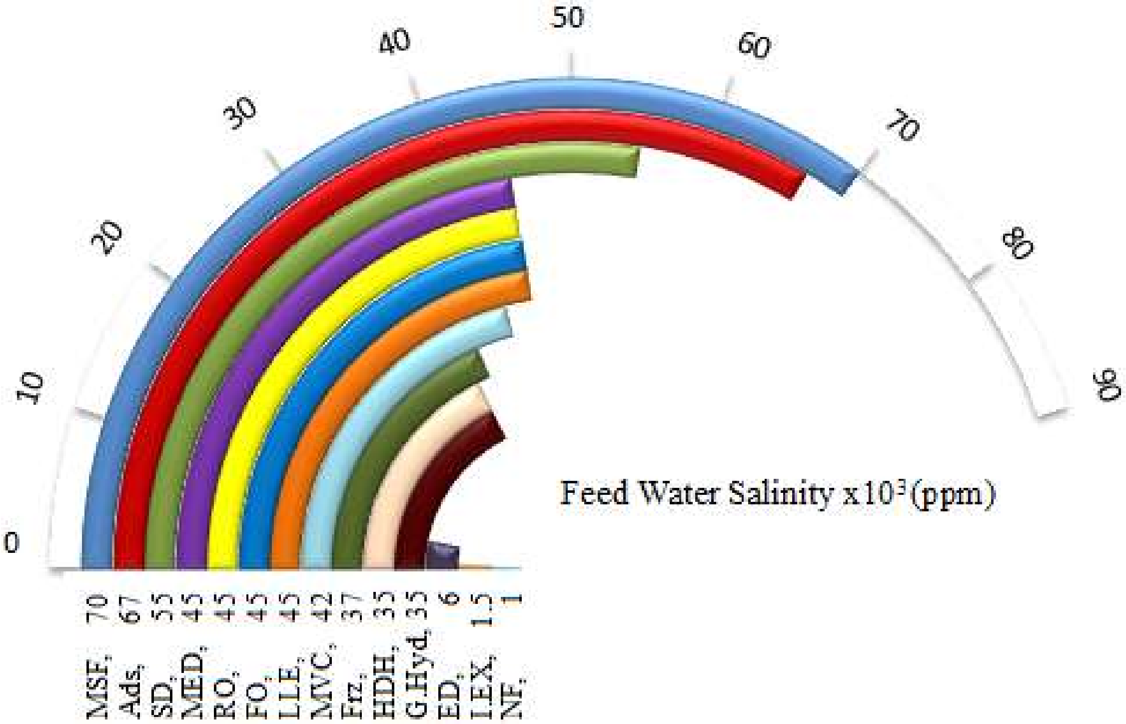

Figure 22. Desalination capabilities of different desalination technologies according to feed water salinity, (Thu, 2010; Mohammad Ameri *et al*., 2009; Shen *et al*., 2014; Ratnayaka *et al*., 2009; Park *et al*., 2011; Lazare, 1982; Kalogirou, 2014; McGovern *et al.,* 2013; El-Nashar, 1985; Mahdavi *et al*., 2011; Altaee *et al.,* 2013)

6.2. Produced water salinity

Figure 23 shows the salinity level of the output water for each desalination technology. It is clear from this Figure that FO, MED, MVC, MSF, RO, Ads and I.Ex produce water with salinity level less than 13ppm, while the remaining technologies produce water salinity level of 100 to 250ppm.

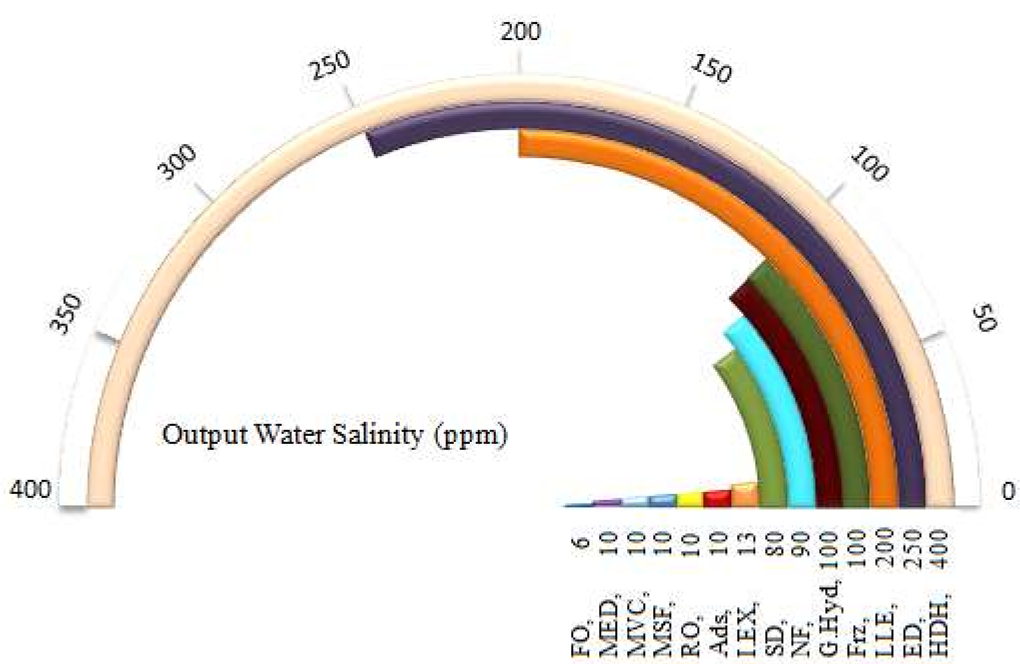

Figure 23. Desalination capabilities of different desalination technologies according to produced water salinity, (Khwaji et al., 2008; Holst, 2007; McCormack and Andersen, 1995; Hahn, 1986; Ratnayaka*et al*., 2009; Lazare, 1982; Ng et al., 2012; Tinos, 2012;JHL, 2009;Mehta*et al*., 2011; Thorsen*et al*., 2006; Chi*et al*., 2012; Djebedjian*et al*., 2007)

6.3. Type and amount of energy required

The type of energy source required to drive the desalination systems is important in determining the overall cost and the environmental impact.MSF and MED systems can use steam coming from either an external boiler, steam power plant or flashed steam from a waste energy source with steam temperature ranging from 75°C (Al-Shammeri and Safar, 1999) to 115°C (Abduljawad and Ezzeghni, 2010). MVC requires mechanical energy to rotate the compressor; this energy is usually obtained from an electric motor or from coupling to a wind turbine (Marcovecchio *et al*., 2010).

HDH systems use heaters for either heating air or water at temperatures from 70 to 95°C. These heaters may be electric heaters, solar water heaters, steam ejectors or geothermal spring (Bourouni *et al*., 2001). SD use solar energy for the desalination processes at temperatures of 100 to 400°C depending on the type of solar system (Qiblawey and Banat, 2008). Freezing systems need mechanical energy to drive the compressor (Rahman *et al*., 2006). RO, FO and NF systems utilize pumps driven by electric motors (Modernwater, 2012). Electric energy is applied in ED systems to produce the required electric field between the anode and cathode. For gas hydrate desalination systems, in addition to the use of a hydrate former, mechanical energy is required to drive the compressor.

The operating pressure of the gas hydrate former rangesfrom 1 to 44 bars depending on the type of hydrate former used (McCormack and Andersen, 1995). Finally, adsorption desalination can utilize low temperature waste heat at temperatures of 55 to 85°C or solar energy by which it can produce fresh water without any fossil fuel input or energy from carbon based fuels (Thu *et al*., 2013)**Error! Reference source not found.**. **Error! Reference source not found.**.

Figure 24 compares the amount and type of purchased energy used in each desalination technology. It is clear from this Figure that apart from the SD technology, the Ads, G. Hyd and I. Ex consumes the least amount of electrical input energy of 1.58kWh/m^3, while Frz and MVC consume the highest electrical input of around 12kWhr/m^3.

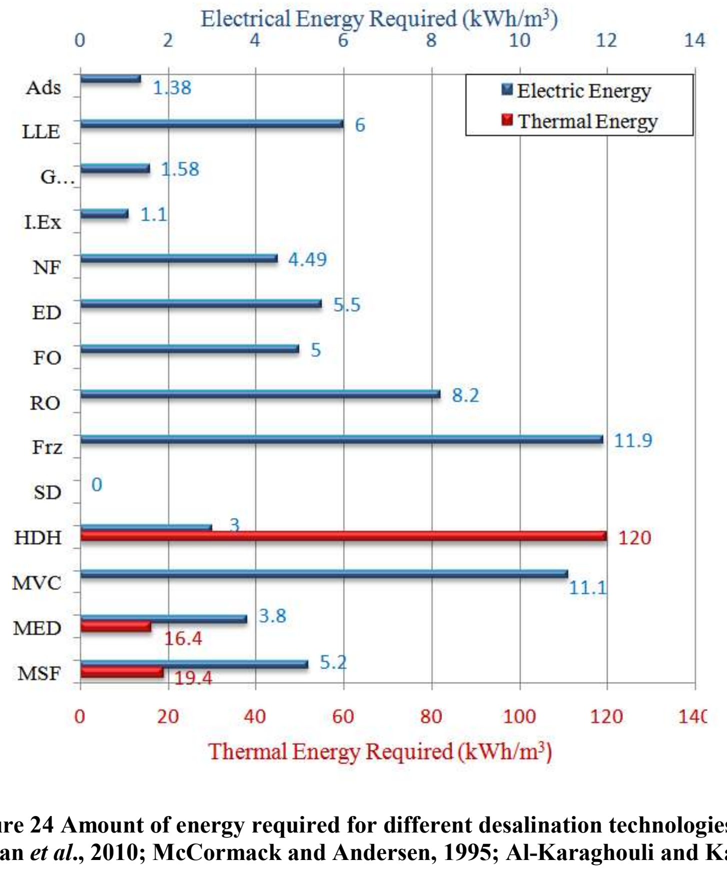

Figure 24 Amount of energy required for different desalination technologies, (Thu, 2010; Narayan *et al*., 2010; McCormack and Andersen, 1995; Al-Karaghouli and Kazmerski, 2013; Chakraborty *et al.*, 2013; Cheng *et al.*, 2013; Narayan *et al.*, 2011; Thomas, 1997; Moon and Lee, 2012; Lubis, 2009; Thanapalan and Dua, 2011)

6.4. Environmental impact

In the previous section, the amount of energy required to operate each individual technology was presented. Using this data, the amount of CO_2 emitted can be calculated. Figure 25 shows a breakdown of the calculated CO_2 emissions for each technology based on emission factor for burning of natural gas of 6.42x10^{-5} tCO_2/MJ (thermal energy) and on CO_2 emission factor for electricity generation of 0.4612 tCO_2/MWh (Chakraborty *et al*., 2013). It can be seen that HDH produces the largest CO_2 emissions of 29.12kg/m^3 while Ads, I.Ex and SD produce the least CO_2 emissions of less than 0.64kg/m^3.

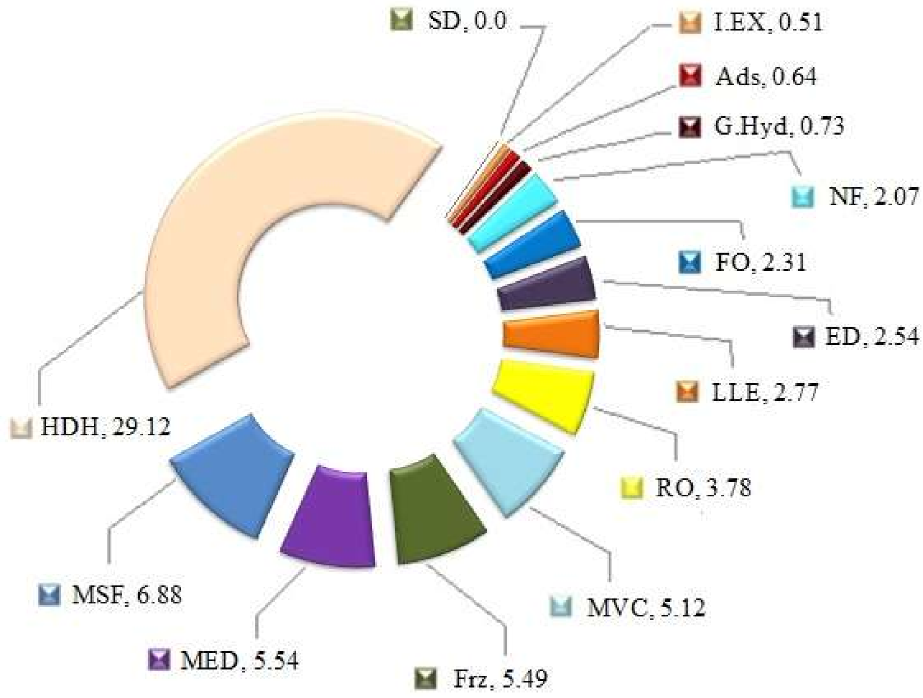

Figure 25 Amount of Released CO_2 for different desalination technologies (kg/m^3)

6.5. Cost

One of the important parameters in selecting desalination technology is the cost. These costs are divided into capital cost and running cost. Many factors affect these costs like plant location, availability of required energy, methods of storing produced potable water, associated labor cost and disposal of produced brine. Because of all these parameters, a rough estimation of these costs is presented in Figure 26 (Mezher, 2011). It is clear from this Figure that Ads can produce potable water with the lowest cost of 0.2$/$m^3$ while the HDH produces potable water at the highest cost of 3.93$/$m^3$.

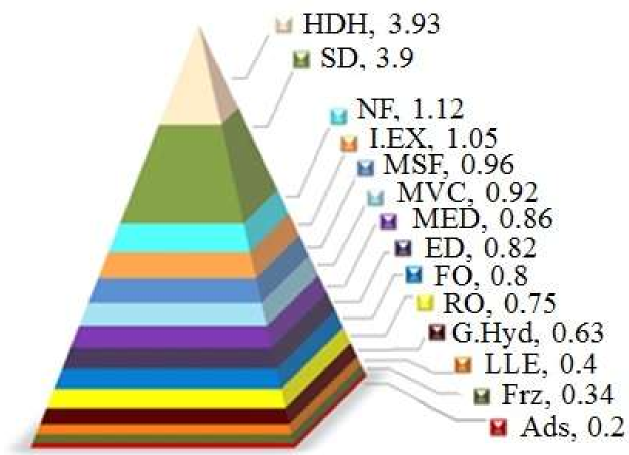

Figure 26. Potable water production cost for different desalination technologies ($/$m^3$), (Thu, 2010; Lazare,1982; Al-Karaghouli and Kazmerski, 2013; Chakraborty *et al.*, 2013; Cheng *et al.*, 2013; Mezher *et al.*, 2011; Banat, 2007; Balch *et al.*, 2012; Eslamimanesh and Hatamipour, 2010; Boysen and Harju, 1999; Miller, 2003; Kim *et al.*, 2013)

7. Conclusions

With the growing of world population, the need for fresh water is increasing. World water resources are mainly salty (97.5%) and fresh water (2.5%).Water desalination technologies offer the means to produce fresh water from saline water abundant in seas and oceans to provide for the worldwide increasing demand for fresh water. Various technologies have been developed to desalinate saline water using various physical concepts with different performance characteristics. This work reviews current desalination technologies and assess their performance in terms of input and output water quality, amount and type of input energy, environmental impact and cost. Although there are some technologies that have low energy requirement and CO_2 emissions like SD and I.Ex, it was concluded that adsorption desalination offers the best overall performance since it can handle feed water with high salinity (up to 67,000ppm) and produce potable water (10ppm) with minimum running cost (0.2$/$m^3$) and low environmental impact (0.6kg/m^3).Therefore, further research is required to develop this technology in terms of developing new water adsorbents and thermally efficient bed designs.

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