Desalination: Conversion of Seawater to Freshwater

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ABSTRACT

Desalination methods are used to convert saline/brackish water to drinkable freshwater. Major processes use either thermal energy (conventional distillation) or pressure energy (Reverse osmosis). Different methods of desalination are discussed and their influence on overall water production has been highlighted. With the increase in appreciation for a green technology, desalination methods using renewable/waste energy are drawing significant attention in recent years. Applying different methods of desalination for coastal areas in Peninsular Malaysia can be very promising in terms of overall public health and economy.

Keywords-Desalination; Freshwater production; waste energy; Reverse Osmosis; Multi-Stage Flashing(MSF); Multi Effect Distillation(MED);Membrane Distillation(MD).

1. INTRODUCTION

In Al-Quran, it is stated "And We sent down from the sky water (rain) in (due) measure, and We gave it lodging in the earth, and verily, We are able to take it away." [1]. Water for living has been the second most pressing concern in the 21st century after population growth. On earth's surface, only one percent of the available freshwater is easily accessible, which is the water found in lakes, rivers, reservoirs, glaciers and underground sources. Also, the groundwater is getting deeply buried with the explosion in world population and excessive concentration level of dissolved salts does not allow it even to be used for industrial applications. Scientists and researchers have explored the possibility of utilizing the biggest water source, the sea, employing various methods of desalination.
Malaysia has been blessed with many natural resources. Abundance of sweet water is one among them. If we look into the scenario of the neighboring country, Singapore, the situation is very much different. They have to strive to find freshwater as the island is surrounded by the sea. Same condition applies for the coastal areas in Malaysia. The water salinity is a major problem and this issue has drawn attention of the water authority recently. Launching a RM 60Million new water desalination plant is Sarawak [2] reflects the necessity of seawater desalination in Malaysia.

2. DESALINATION

Natural desalination has been occurring on earth since the creation of the seas. Water evaporates from the sea and then condenses to form pure rain water. Desalination has been practiced by man in the form of distillation for over 2000 years. In the history of human civilization, the process dates back to the 4th century B.C. when Greek sailors used an evaporative process to desalinate seawater [3]. In the recent past, the oil discovery in the arid region of Arabian Gulf countries made significant contribution in development of thermal desalination plants. By mid-2007, desalination processes in Middle East countries accounted approximately 75% of total world capacity of desalinated water [4].

Although there are a number of ways to convert seawater to fresh water, a common overall process applies to all schemes. Actual nature of each step would depend on the desalination method used. Figure 1 shows the steps involved in the process.

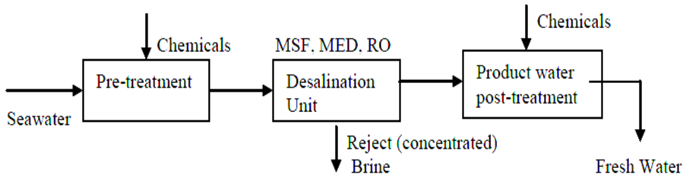

Figure 1. Schematic diagram of a desalination process [5].

The nature of the pre-treatment depends on the type of intake system and the extent of pollution in the surrounding sea. The supply of water directly from shallow bays near the shore may provide seawater with high contents of bacteria, algae and suspended solid. Normally, seawater drawn from open ocean is cleaner and requires less pre-treatment steps. Pre-treatment of raw feed water is necessary to preserve the life and reliability of the desalination equipment. As stated earlier, there are a number of methods available for the conversion of seawater to fresh water. Irrespective of the method of conversion process, the product water should have a total dissolved solid (TDS) content of less than 500 ppm [6]. Table 1 shows the typical constituents of seawater and potable water. This product water is not suitable for direct human consumption and some form of post-treatment is necessary to control sodium and chloride ions, and its pH.

Large-scale thermal desalination requires large amounts of energy and special infrastructure that makes it fairly expensive compared to the use of natural fresh water. As a result, recently, membrane processes are taken into consideration and these processes rapidly grew as a major competitor to thermal desalination in the later years because of lower energy requirements, easier maintenance, smaller area, quicker start up and cost effectiveness, and thus leading to a reduction in overall desalination costs over the past decade. Most new facilities operate with reverse osmosis (RO) technology which utilizes semi-permeable membranes and high pressure to separate salts from water. However, reverse osmosis process is not well-suited for hot or warm water as the membrane performance deteriorates with temperature above 40^{o}C.

Table 1. Typical constituents of seawater and potable water [7]

Constituents	Seawater (mg/L)	Potable Water (mg/L)
Barium	0.02	1.0
Calcium	412	75
Carbonates	28	150
Chloride	19500	250
Copper	$1x10^{-4}$	1.0
Fluoride	1.3	1.5
Iron	0.002	0.3
Lead	$5x10^{-7}$	0.05
Magnesium	1290	50
Manganese	$2x10^{-4}$	0.05
Mercury	$3x10^{-5}$	0.001
Nitrates/Nitrogen	11.5	10
Phosphates	0.06	0.4
Potassium	380	10
Silica	2	7.1
Sodium	10770	200
Sulphates	905	400
Total dissolved solid	33387 (ppm)	500 (ppm)
pH	8.0	6.5 - 8.5
Turbidity	3 - 15 NTU	5 NTU

3.DIFFERENT DESALINATION METHODS AND THEIR INFLUENCE IN WATER PRODUCTION

Desalination processes can be broadly classified into two major groups: (1) desalination with change in phase and (2) desalination without the phase change. Thermal desalination, freezing and carrier gas processes are example of the first one and RO is an example of the latter. Figure 2 provides a quick reference to all these processes:

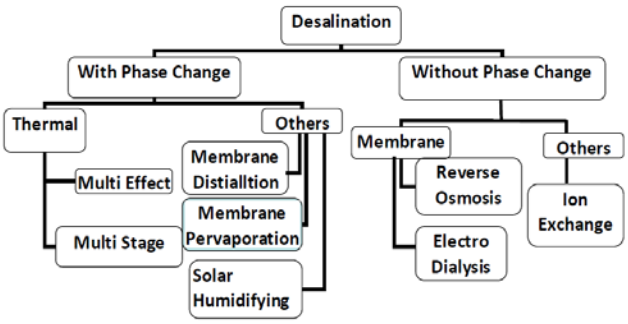

Figure 2: Classification of desalination Processes

Some of the desalination processes are most widely used like Multi-stage Flash(MSF), Multiple-effect Distillation (MED) and RO; while some are not commercially available yet like Membrane Distillation (MD), electro-dialysis or membrane pervaporation. The widely used thermal desalination processes are basically distillation processes that convert saline water to vapour and then the vapour is condensed to obtain the freshwater. Although membrane technologies like RO are invading quickly, the thermal distillation processes produce the largest amount of freshwater in the Middle Eastern countries due to cheap cost of fossil fuel in that region. Figure 3 summarizes the capacity of different techniques for treating Seawater and brackish water worldwide, while Table 2 highlights on the energy and cost comparison.

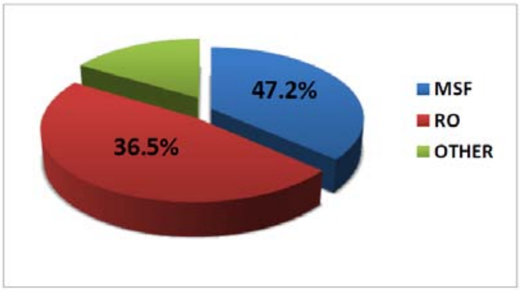

Figure3.Contribution of different desalination processes[8]

Table 2: Energy, cost and capacity of major desalination processes

	MSF	MED	RO
Energy (kWh/m^3)	4 [9]	1.8 [9]	5 [10]
Cost (USD/m^3)	2.185 [11]	1.87 [12]	0.55 [13]
Maximum capacity reported (m^3/day)	280000 [14]	13626 [15]	45400 [9]

4. DESCRIPTION OF DIFFERENT DESALINATION METHODS

This section includes a description of MSF, MED, RO and other desalination processes available for the conversion of seawater to freshwater.

4.1.Multi-stage flash distillation system (MSF)

Multistage flash distillation involves heating saline water to high temperatures and passing it through decreasing pressures to produce the maximum amount of water vapour that eventually produces the freshwater. The heat recovery is established using this distilled water as the heating source for the incoming feed and regenerative heating is utilized to flash the seawater inside each flash chamber. The latent heat of condensation released from the condensing vapour at each stage gradually raises the temperature of the incoming seawater. There are three sections in an MSF plant: heat input, heat recovery, and heat rejection sections. The brine heater heats up the sea water using low pressure steam available from cogeneration power plant, such as, a gas turbine with a heat recovery steam generator or from a steam turbine power plant. The seawater is fed on the tube side of the heat exchanger that is located on the upper portion of evaporator. Thus, the seawater heated by the condensing steam enters the evaporator flash chambers. There are multiple evaporators, typically containing 19–28 stages in modern large MSF plants. The top brine temperature (TBT) range is usually within 90 to 120°C. Although higher efficiency is observed by increasing TBT beyond 120°C, scaling and corrosion at high temperature affects the process significantly [16]. To accelerate flashing in each stage, the pressure is maintained at a lower value than that in the previous stage. Hence, the entrance of heated seawater into the flash chamber causes vigorous boiling caused by flashing at low pressure.

The flashed water vapour is then cooled and condensed by cold seawater flowing in tubes of the condenser to produce distillate. The distillate produced and collected in each stage is cascaded from stage to stage in parallel with the brine, and pumped into a storage tank.

Figure 4 shows the process of MSF desalination below.

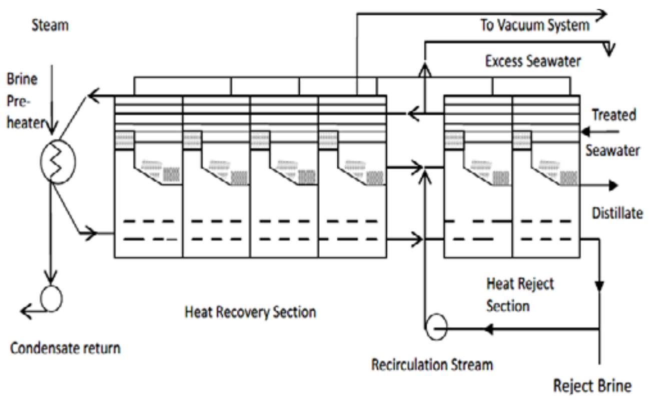

Figure 4. The MSF desalination process [7]

4.2.Multi-effect desalination system (MED)

The multiple-effect distillation (MED) process is the oldest but a very efficient desalination method. Instead of the term “stage”, the multiple evaporators inside an MED plant are called “effects”. In this method, the seawater undergoes boiling in multiple stages without supplying additional heat after the first effect. The evaporators are arranged either (a) horizontally [horizontal tube evaporator (HTE) with evaporated seawater sprayed outside the tube while the heating steam is condensed inside the tubes] or (b)vertically [long vertical tube evaporators (VTE) with boiling seawater falling film inside the tube while the heating steam is condensed outside the tubes] [17]

For the first effect, the seawater gets preheated inside the evaporator tubes and reaches boiling point. The tubes are heated externally by steam from a normally dual purpose power plant. Only a portion of the seawater applied to the tubes in the first effect is evaporated. The remaining feed water is fed to the second effect, where it is again applied to a tube bundle. These tubes are in turn heated by the vapour created in the first effect. This vapour is condensed to produce fresh water, while giving up heat to evaporate a portion of the remaining seawater feed in the next effect at a lower pressure and temperature.

Figure 5 shows the schematic of an MED process. The MED specific power consumption is below 1.8 kWh/m^3 of distillate, significantly lower than that of MSF, which is typically 4 kWh/m^3. [9].

To improve the efficiency of the MED process, a vapour compressor is added before the first stage to boost up energy carried by the vapour. This process is termed as vapour compression (VC). Normally, it is recommended to use multiple stages in this process, as VC system with multiple effects gives increased performance ratio, decreased power consumption and maximum utilization of heating source [18].

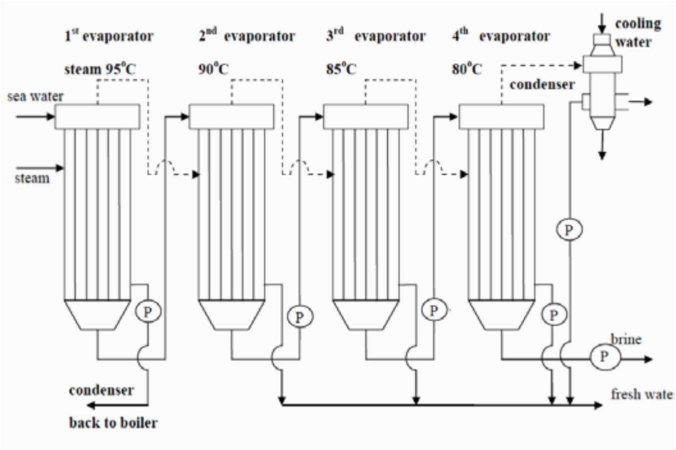

Figure 5. The MED process [19]

4.3. Reverse Osmosis Desalination

This membrane process does not involve phase change and the permeate (which is the product water) passes through a hydrophilic membrane under certain applied pressure, which is higher than the osmotic pressure of seawater. Thus, water flows in the reverse direction to the natural flow across the membrane, leaving the dissolved salts behind with an increase in salt concentration. The major energy required for desalting is for pressurizing the seawater feed which is recovered by pressure exchanger (PE). In the pressure exchanger the energy contained in the residual brine is transferred hydraulically. This reduces the energy demand for the desalination process significantly and thus the operating costs. The pressure needed for separation ranges within 50 bars (seawater) to 20 bars (brackish water). [20]. The osmotic pressure is dependant on the feed concentration. A typical large seawater RO plant consists of four major components namely a) feed water pre-treatment, b) high pressure pumps, c) membrane separation, and d) permeate post-treatment. Figure 6 shows the RO desalination system. The RO plant energy consumption is approximately 6–8 kW h/m^3 without energy recovery and with an energy recovery from the high pressure side, the energy consumption reduces to to 4–5 kW h/m^3 [10]. RO has its limitations too. The major problem faced by RO plants is in the pre-treatment area and the membrane sensitivity to fouling. Also, the feed temperature must not exceed 40^{o}C to avoid thermal damage of the membrane.

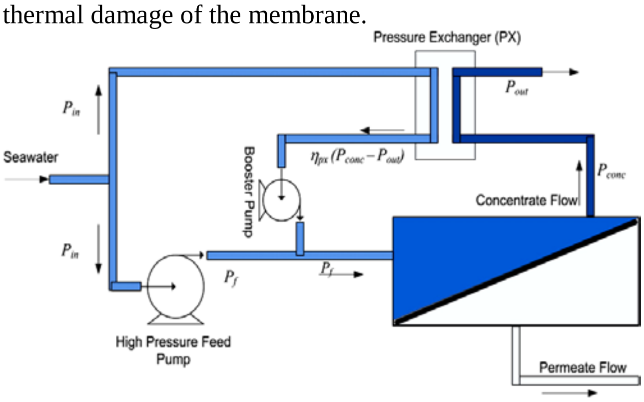

Figure 6. The RO desalination process [21]

4.4. Other low energy desalination methods

Beside these commercially available energy intensive desalination processes, some other methods have drawn attention recently based on their low energy requirement. Among them, Membrane Distillation (MD), Adsorption Desalination (AD), Membrane Pervaporation etc are examples of these recent techniques.

4.4.1 Membrane Distillation

With the burning issues of global warming, there has been a need to utilize the low grade waste heat before they can be released to the environment and a somewhat recent technique developed in the 60's called Membrane Distillation (MD) shows good potential in utilizing low grade heat and producing fresh water from saline water. It uses the difference in partial pressure to produce vapour from a feed solution that gets condensed either by a direct cold distillate stream or a cold surface, and produces freshwater. To maintain the interfacial barrier between the two dissimilar temperature fluids, a hydrophobic membrane is required so that only the vapour can travel to the cold side. It is capable of producing distillate at even 45°C at ambient pressure [22]. Because of simple infrastructure, operation and maintenance, this process has been able to draw significant attention of the researchers in the recent years. Figure 7 shows schematic of an MD setup.

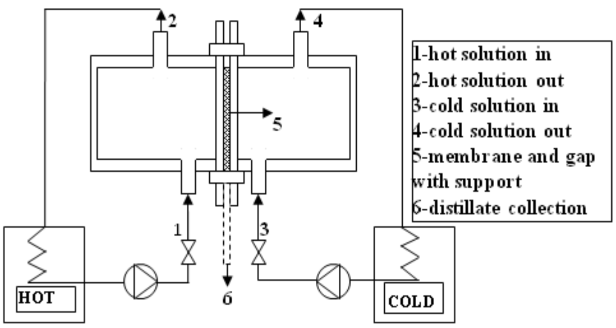

Figure 7.Schematic Diagram of an MD setup [22]

4.4.2.Adsorption desalination (AD)

A silica gel adsorbent (desiccant) is used as a medium between an evaporator and a condenser to reject and facilitate latent heat of evaporation. The silica gel is arranged around tubes in packed form and contained within beds to be cooled during adsorption or heated during desorption by water. The process temperature is within a maximum of 85°C for the beds and 20°C for the beds and the condenser. The evaporator requires a heat source to maintain feedwater temperature.

4.4.3.Membrane pervaporation

Pervaporation involves the separation of two or more components across a membrane by differing rates of diffusion through a thin polymer and an evaporative phase change comparable to a simple flash step. A concentrate and vapor pressure gradient is used to allow one component to preferentially permeate across the membrane. A vacuum applied to the permeate side is coupled with the immediate condensation of the permeated vapors.

5. UTILIZATION OF RENEWABLE/WASTE ENERGY IN DESALINATION

As the major desalination processes involves heating of the brine, there is an opportunity to utilize solar energy (renewable) or waste heat from different thermodynamic cycles(such as refrigeration and air conditioning). A recent application [23] using both solar and condenser waste heat was able to increase the COP of a solar assisted heat pump cycle with an MED system to 5.8. For the desalination process, the Performance Ratio obtained was 1.2 with a production of maximum 30 l/hr.

It was reported applying marine engine cooling water in an MD process [24] and it was possible to design a system capable of producing freshwater at 0.18kWh energy input.
The AD cycle is found to give the lowest energy consumption at about 1.5 kWh/m^3, equivalent to US$0.227 per m^3,while the highest production cost is from the MSF at US$0.647 [25].

6. CONCLUSION

This paper provides an overview of different desalination processes and their appropriate applications. Although desalination is not yet very popular in Malaysia because of the abundance natural supply of sweet water by the grace of Allah, although it has an excellent prospect for the coastal areas of peninsular Malaysia. It can be very promising with the aid of waste heat / solar energy to get freshwater from seawater at a much cheaper price. Future planning of water treatment must focus on exploring different desalination methods to find a better way to resolve water issues.

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