THE ECONOMICS AND PERFORMANCE OF DESALINATION PLANTS

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Contents

Summary

In this chapter the technical and economic features of the four major seawater desalination processes, MSF, MED, MED-TVC and SWRO, are reviewed. Each process is described in some detail and the basic mathematical relations used for estimating its performance are outlined. Economic models developed for the purpose of estimating the water cost for each process were also introduced. The range of energy requirement for each desalination process is presented and a comparison of the energy requirement is made for the major desalination processes. A number of available commercial computer models for economic evaluation of desalination processes is introduced. The main features of each computer model is explained and sample economic calculations for each desalination process is made to show, in detail, how the unit water cost can be estimated. Comparison of the water cost of the different desalination processes was also carried out.

1. Introduction

The promise of desalination to rid the world of water scarcity has been touted for nearly 50 years. During this period, public and private investment in developing and improving desalination technology has totaled more than a billion dollars. Although much progress has been made and there have been successes in developing water supplies in very dry locales and regions, the promise remains largely unfulfilled. The explanation lies with the fact that, although the process costs have been reduced, the total costs of desalination, including the costs of planning, permitting, and concentrate management, remain relatively high, both in absolute terms and in comparison with the costs of other alternatives.

In assessing the future prospects and promise of desalination technology, it is particularly important to examine the current and prospective financial and economic circumstances that are likely to surround the technology as it develops. An examination of the structure of desalination costs and of the determinants of those costs is important in identifying areas in which research might be pursued with the greatest effect. A consideration of the availability and costs of alternative supplies helps to place the future role of desalination in perspective. Finally, issues of reliability, water quality, and environmental impacts need to be understood if the costs and benefits of desalination technology are to be broadly understood.

In this report the technical and economic features of the four major seawater desalination processes, MSF, MED, MED-TVC and SWRO, are reviewed. Each process is described and its mathematical model is developed and solved. An economic model was also developed for the purpose of estimating the water cost for each process. Comparison of the water cost of the different processes was carried out.

2. Description of the Seawater Desalination Processes

2.1. Multi Stage Flash (MSF) Distillation Process

There are two different configurations of the multistage flash process (MSF): the brine recirculation and the once-through versions. The brine recirculation MSF process is illustrated in Figure 1. In this process, seawater is taken into the plant and fed through the heat rejection section. This water passes through a series of heat exchangers, raising its temperature. The water then enters the first recovery stage through an orifice and in so doing undergoes a decompression to a pressure below its saturation pressure. As the water was already at the saturation temperature for a higher pressure, it becomes superheated and has to give off vapor to become saturated again at the lower pressure. This is known as ‘flashing’. The vapor produced passes through a wire mesh (demister) to remove any entrained brine droplets and then into a heat exchanger where it condenses, giving up its energy to heat up the upcoming brine flow. This process of decompression, flashing and condensation is then repeated all the way down the plant by both the brine and distillate streams as they flow down through the subsequent stages which are at successively lower pressures.

As shown in Figure 1, the process can have any number of stages. Large modern plants usually have between 14-20 heat-recovery stages. Process efficiency is enhanced by re-circulating some of the brine discharge and mixing it with the incoming seawater. This is done in the heat rejection section (2-4 stages) and requires a brine recirculation pump. All of the large plants are of this type. For small plants the heat rejection section can be removed. This reduces the efficiency of the system but simplifies it considerably. It is the simplest form of the MSF process and is favored for small plants.

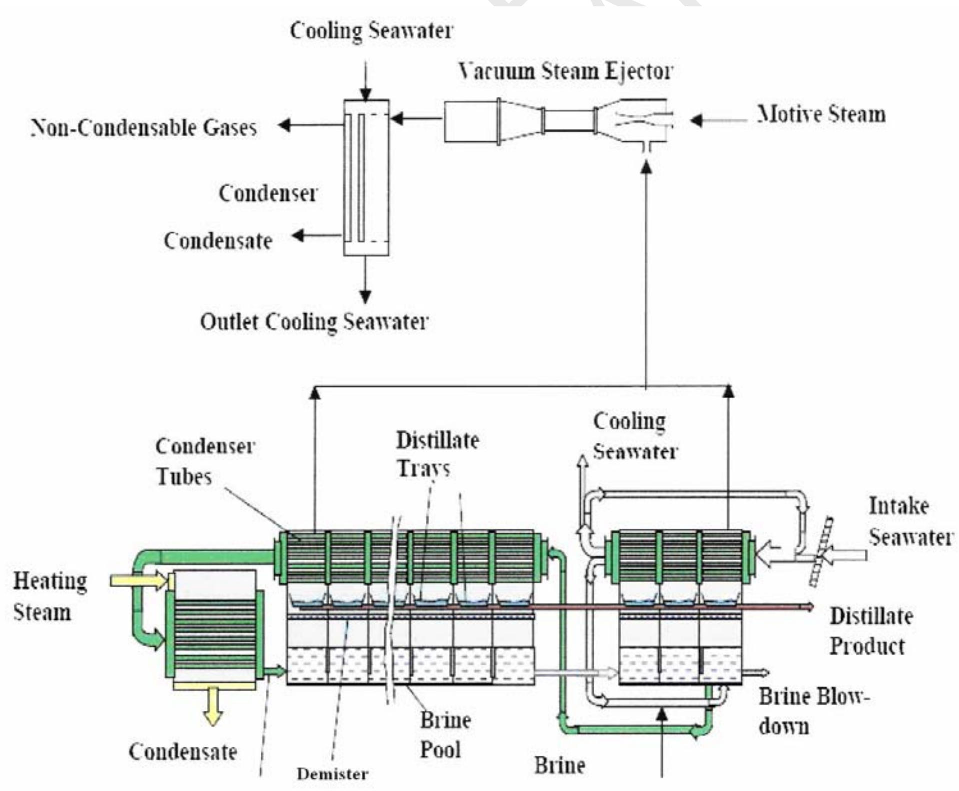

Figure 1 . Brine recirculating multi-stage flash (MSF) process

All evaporation distillation processes can be prone to scaling unless action is taken to prevent it. Scaling is caused by the solids in solution coming out of solution because of increased concentration or in some cases because of the increased temperature affecting compounds with inverse solubility.

Figure 2 shows a battery of MSF plants installed at Jubail in Saudi Arabia in the mid eighties.

The units were shipped in to site on a barge in one piece. Technical advances and cost reductions made over the years relate mainly to improved corrosion resistance by the use of expensive alloys, increase in size and improvements in control technology and scale inhibitors.

Figure 2. 2,500 m^3/day units at Jubail, Saudi Arabia

The process is relatively simple to operate and once set up, is stable in operation. Because of the thermal inertia of the plant and vacuum considerations, the process is best suited for continuous operation. As seawater is corrosive to carbon steel, there is an increasing tendency to construct plants, particularly small ones, using stainless steels and copper nickel alloys. The process is not usually deemed suitable for very small capacities although some small units of 10 - 20 m^3/day have been constructed to operate in conjunction with renewable energy systems. Figure 3 shows a schematic for the MSF once- through MSF process. As is shown the system includes a brine heater, the flashing stages, the vacuum ejector, chemical addition pumps, and the feed screens. The following is the description of process operation:

- The feed is pumped through a large duct, which contains the coarse screens. The screens remove large suspended solids. This is necessary to prevent fouling and blockage of the pumping units and the condenser tubes.
- The feed is deaerated to remove dissolved gases, i.e., oxygen, nitrogen, and carbon dioxide. If these gases are not removed, it is released in the flashing stages due to heating and reduction in pressure. The released gases have low thermal conductivity

and would reduce the heat transfer rate around the condenser tubes. Also, carbon dioxide and oxygen may promote corrosion reactions in various locations within the flashing stage. The deaerator may have vertical or horizontal configuration, which is equipped with spray nozzles or trays. Deaeration is accomplished by heating steam, which results in increase in the feed temperature and as a result reduces the gas solubility in the feed water. Also, the heating steam contains no dissolved gases, this generates a gradient for desorption of the dissolved gases into the steam in order to achieve equilibrium.

- Other treatment chemicals are then added to the feed water. The chemicals include antiscalent, chlorine, and antifoaming. The antiscalent/antifoaming agents have to be added at the proper dosage otherwise scaling or excessive foaming may occur in the high temperature stage. The chlorine is added to the feed water to prevent biofouling inside the condenser tubes.
- The deaerated feed water flows through the condenser tubes starting from the cold end or the last stage. The feed seawater temperature increases as it recovers the latent heat of the flashed off vapor. The feed seawater is heat to the desired top brine temperature in the brine heater.
- The feed seawater flows on the tube side of the brine heater. This is necessary to simplify cleaning and removal of fouling and scaling material. This is achieved through use of on-line ball cleaning as well as acid cleaning. The on-line ball cleaning is performed on daily basis; however, acid cleaning is made at much longer intervals (close to six months or one year interval). The on-line ball cleaning and acid cleaning are also applied to the condenser tubes.
- The heating steam flows on the shell side; where more than one inlet is used to achieve uniform temperature distribution within the heater. The steam condensate is collected in a small well at the bottom of the heater. The well generates sufficient hydraulic head to prevent vapor flashing within the condenser pump.
- The hot feed seawater then flows through the stages, where vapor flashing takes place. In each stage a small amount of water vapor is formed and it condenses around the condenser tubes.
- The distillate product flows in the distillate trays across the flashing stages. The distillate product flashes off generating a small amount of vapor as it flow from one stage to another. This flashing process also accounts for further heating of the feed seawater.
- In the last stage the brine blow down and distillate are collected, where the brine blow down is rejected back to the sea and the distillate is treated further through chlorination and adjustment of its pH value.
- The vent lines shown in the figure are attached to the vacuum steam ejector, which removes the non-condensable gases from the flashing stages. The outlet stream from the ejector is condensed to recover most of its moisture content; the remaining gases and uncondensed vapor are then vented to the ambient air.
- Sufficient hydraulic heads should be made between the outlet distillate and brine blow down and the pumping units. This is to prevent vapor flashing from these warm streams.

The MSF plants are controlled by single input/output control system. Controlled variables include temperatures of heating steam, brine entering the first flashing stage, and brine in the last stage. The brine level in the last stage is controlled to prevent vapor flow through between flashing stages. Also, the levels of the distillate product and heating steam condensate are adjusted to generate sufficient head that prevents flashing within the pumping units. Another measured system parameter is the product salinity, where its increase might result in discard of the distillate product and subsequent system maintenance, which may include cleaning of the condenser tubes or the demister.

The pumping units used in the once through system include pumps for feed, brine blow down, distillate product, steam condensate, chemicals, and ejector condensate. The pumps of the feed and brine blow down streams are very large, because, both streams are close to ten times that of the distillate product. For example, a plant with a production rate of 30,000 m^3/d, would require pumping units that handles 300,000 m^3/d of feed seawater and 270,000 m^3/d of brine blow down. The remaining pumping units have a much smaller capacity. For this same illustration, the heating steam condensate pump will have a capacity of 3000 m^3/d and the ejector condensate pump will be limited to 1000 m^3/d.

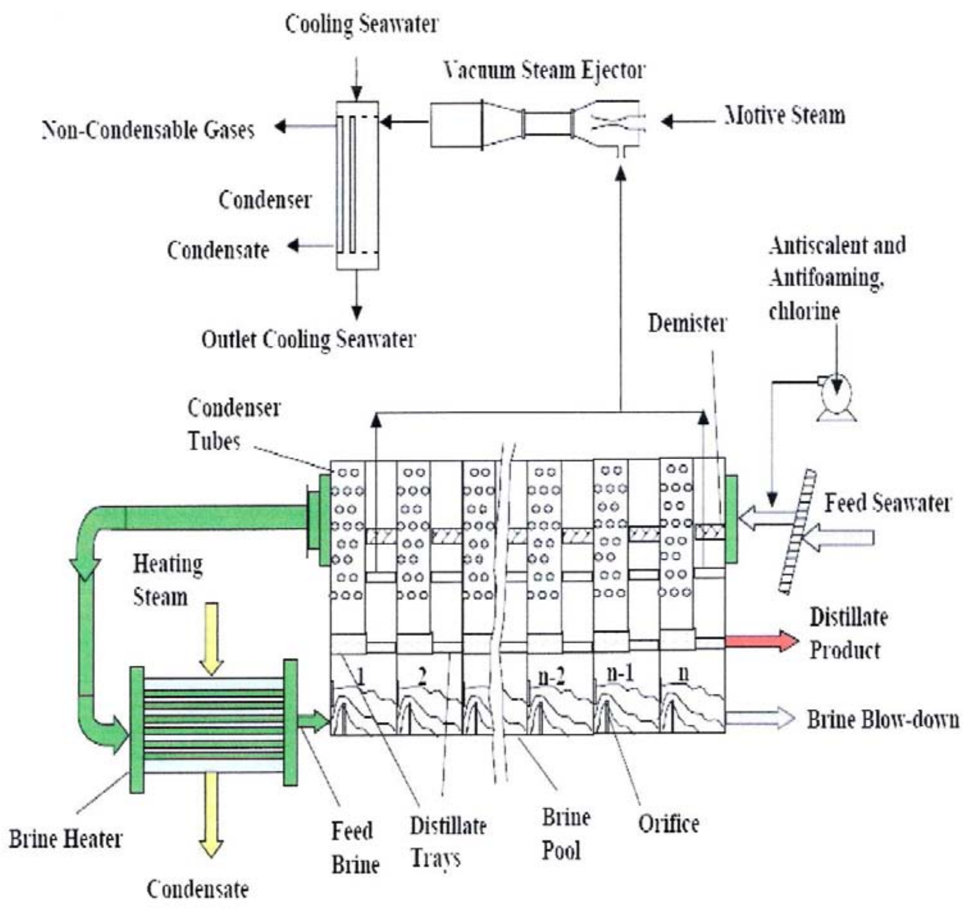

Figure3 . A once-through MSF process

2.2. Multiple Effect Distillation (MED) Process

The Multi-Effect Boiling (MEB) process is used widely in the chemical industry where the process was originally developed. MEB was the first process to be used for seawater desalination and involved submerged tubes in which the seawater was boiled. In recent years however there has been renewed interest in Multi-Effect Distillation (MED) and plants of up to 20,000 m^3/day have been built. MED is thermodynamically the same as MEB but the mechanism of heat transfer is different. In MEB the condensing steam transfers its heat through the tube to a thin film of brine where evaporation takes place. The process has the potential of giving higher performance ratios (PR).

PR of up to 20 has been achieved. The process also uses less electrical power for pumping and the new designs are lighter in weight. A number of successful large scale plants using thermo-compression and with performance ratios of 8 have been built in the Gulf and elsewhere. In the MED process vapor is produced by two means, by flashing and by evaporation. The majority of the distillate is produced by evaporation (Figure 4). The MED process usually operates on a once through system having no large mass of brine recirculation round the plant. This reduces the pumping requirements and has a major (beneficial) effect on the scaling tendencies in the plant.

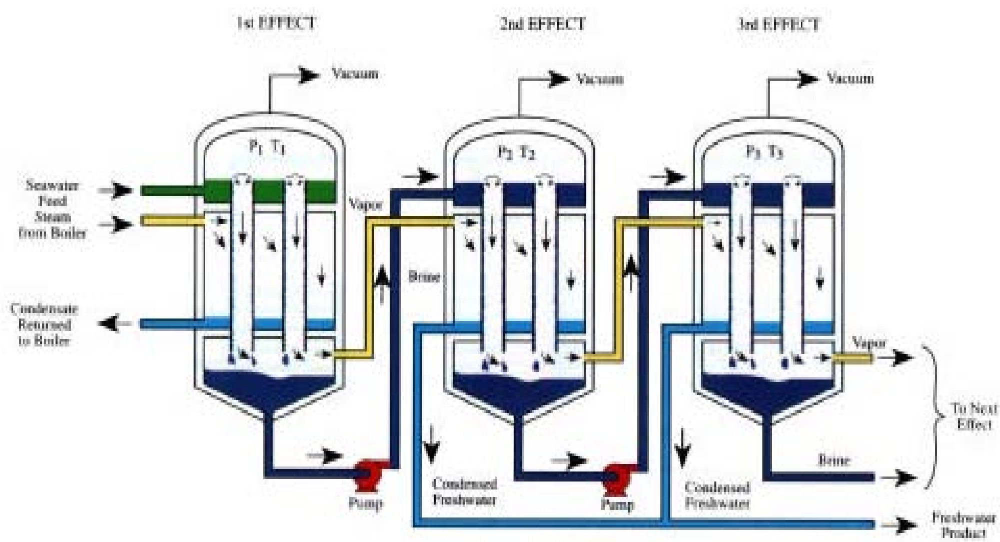

Figure 4 . MED evaporator having 3 effects

In the MED plant shown above, the incoming feed goes into the first effect where it is heated to boiling point. Some of the liquid evaporates and the resultant vapor is used to heat the liquid which passes from the first effect to the second. The feed to the second effect flashes as it enters the second effect because it is at a slightly lower pressure. This process continues down the successive stages of the plant. This is a simple MED plant. In commercial plants the incoming feed is passed to the last effect first and flows up the plant in the reverse direction. The feed is passed through a series of inter-stage feed heaters (feed heaters not shown above) which also serve as partial condensers for the vapor. After passing through the last of these, it enters the top “effect” where the heating steam brings it up to its boiling point and then evaporates a significant portion of it. The vapor produced is then condensed, in part, in the feed heater and in part by providing the heat supply for the second effect which is at a lower pressure and receives its feed from the brine of the first effect. This process is repeated all the way down the plant. The distillate also passes down the plant. Both the brine and the distillate flash as they travel down the plant due to the progressive reduction in pressure.

Unlike MSF, the performance ratio for an MED plant is more rigidly linked to, and cannot exceed, the number of effects in the plant. For an instance, a plant with 13 effects might typically have a performance ratio of ten. However, an MSF plant with a performance ratio of ten could have 13 to 35 stages depending on the design. There are many possible variations of MED plants, depending of the combinations of heat transfer configurations and flow sheet arrangements used. Early plants were of the submerged tube design (MEB), and only used two or three effects, and so had small performance ratios. Modern systems have got round the problem of hydrostatic head by making use of thin film designs with the feed liquid distributed on the heating surface in the form of a thin film instead of a deep pool of water. Such plants, which are known as Multi-Effect Distillation (MED) plants, may have vertical or horizontal tubes. In the long tube vertical (LTV) plants (Figure 5) the brine boils inside the tubes and the steam condenses outside. In the horizontal tube falling film (HFF) design the steam condenses inside the tube with the brine evaporating on the outside. The use of horizontal tubes lends itself to a stacked design where effects are built one on top of the other with gravity providing the motive force to transfer liquid to successive effects. A typical arrangement is shown in. Such designs are suitable for small capacity high performance units.

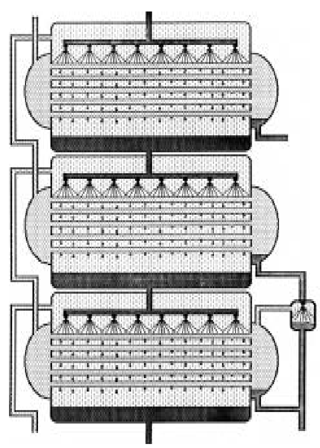

Figure 5 . MED evaporator having 3 stacked effects

MED plants commonly have performance ratios as high as 12 to 14 but can be made higher. Actual performance ratios are determined by optimizing capital cost against operating costs. Small single and multiple effect units are available. As with all thermal processes, it does not lend itself to intermittent use. High performance units require many effects which increases manufacturing costs. The process usually requires inter-stage pumps to transfer the brine through the plant. This increases the maintenance costs. The process can give lower capital costs, lower power requirements and higher thermal performance than conventional MSF and consequently there is a revival of interest in this technology. It also can be adapted for thermal re-compression of steam.

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Biographical Sketch

Ali M. El-Nashar received the B.Sc. (Mech. Eng.) from Alexandria University (Egypt) in 1961 and Ph.D. (Nuclear Engineering) from London University (UK) in 1968. He has been a faculty member at several universities in Egypt, UK and USA and was appointed professor of mechanical engineering at Florida Institute of Technology (USA) and Mansoura University (Egypt). He was a research fellow at Clemson University (USA) during the period 1971 to 1976. He has worked as consultant for different industrial and UN organizations among which Dow Chemical Co. (USA), Ch2M-Hill Co. (USA), Science Application Co. (USA), UNEP, Technology International Co. (USA). He is member of the ASME, ISES and IDA and editor of the International Desalination and Energy journals. He has worked at the Research Center of the Abu Dhabi Water and Electricity Authority (UAE) as manager of the desalination and cogeneration section which pioneered development work on solar desalination for ADWEA for 20 years. He has been associated with the International Centre for Water and Energy Systems, Abu Dhabi, UAE.