MULTI-EFFECT DISTILLATION (MED)

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Summary

The development of desalination plants in recent years and the estimation of increased trends in desalination directions are increasing the interest in understanding desalination plants currently in use. The cost of desalinated water is still high for many people, so there is a need to learn how to reduce costs as well as understand how the techniques work before trying to develop new technologies.

This chapter describes the subject of Multi-Effect Distillation (MED). The technology, which belongs to the field of evaporation techniques, is explained in detail and different designs are included. Design equations are also given based on heat balance, flow configuration and heat transfer mechanisms in the system. Related subjects such as energy needed, the energy source, environmental issues, operational technologies and most common problems are also explained. A comparison with other techniques and recommendations for future improvements are given.

1. Introduction

The demand for fresh water has increased significantly since 1990 for many reasons, including, on the one hand, the increase in world population accompanied by the increase in standards of living, and, on the other hand, global warming followed by climate changes and desertification. Governments and water industries are seeking different solutions for better utilization of available water, thereby increasing the efficiency of growth crops, solutions for better wastewater treatment, and the development of new water sources and improved desalination techniques.

Many desalination techniques were considered over the years. Some survived the economic battle and are currently in use in different places around the globe. Others did not make it, yet are being reviewed from time to time in order to seek possible better techniques. Two main directions are used for industrial water production: thermal techniques and membrane-based techniques. Thermal techniques include the freezing technique that was abandoned and current techniques that are still responsible for more than 50% of the world desalination consumption: Multi-Stage Flash (MSF) evaporation, which is still the most commonly used desalination technique, and Multi-Effect Distillation (MED), with a variation as vapor, thermal or mechanical compression, where the differences are in energy source and recovery (Awerbuch, 1997).

The MED technique is the most sophisticated evaporation desalination technique (Ophir & Weinberg, 1997). It is based on know-how in fluid mechanics of falling films, as well as on the understanding of heat transfer mechanisms and the phenomena of a double film of condensing vapor on one side of the heat transfer surface and the evaporation of falling film without boiling on the other side. This chapter aims at describing the technology related to the MED process.

2. Desalination Techniques

Many desalination processes were proposed over the years; only a few survived the crucial road to produce the cheapest, yet most valuable, product on earth – water. The most successful techniques are summarized briefly below (Porteous, 1975; Buros et al., 1981; Semiat, 2000; El-Dessouky & Etouney, 2002).

2.1. Membrane Processes

Membrane techniques for water desalination are based on different types of molecular level filters – membranes. The most common technique that aims at taking over the entire market of desalination processes is reverse osmosis.

2.1.1. Reverse Osmosis (RO)

Desalination with reverse osmosis membranes is a process whereby saline water under pressure is transferred along a membrane. The pressure applied is high enough to overcome the osmotic pressure of the dissolved salt in feed solution. The osmotic pressure of a solution is proportional to the concentration of the dissolved matter, salts in water, starch or sugar, etc. (Faller, 1999). Salts rejected by the membrane are removed from the membrane with the flow of concentrated solution while fresh salt solution is fed to the membrane. The permeate – the fresh water product – exits the lower pressure side of the membrane.

2.1.2. Nano-Filtration

Nano-Filtration is based on a loose membrane that allows partial passage of monovalent ions (mainly Na^+ and Cl^-) while partially rejecting the bivalent ions. It is used mainly in the desalination of brackish water of low salt concentration. Currently, the cost of these membranes is similar to the cost of RO membranes, so there is not much incentive to prefer these membranes over RO membranes.

2.1.3. Ultra-Filtration and Micro-Filtration

Ultra-Filtration and Micro-Filtration membranes contain large pores that allow the passage of free salts while preventing the passage of different sized suspended matter, down to nano-sized particles and colloids passing through the membranes, depending on pore size. These membranes are used mainly for wastewater treatment and have started to take their place in the pre-treatment of water along with other desalination techniques.

2.1.4. Electro-dialysis

Electro-dialysis is based on the application of an electrical field across a pair of ion-selective membranes, causing the different ion salts to move through the membranes into a concentrated solution, leaving behind a diluting solution. Here, unlike other desalination technologies, the salts are removed from the feed water. The feed water should be free of suspended solids, organic matter and non-ionic contaminants that accumulate in the product (Thampy et al., 1999).

While reverse osmosis may be used for all types of salt water, the nano-filtration and electro-dialysis techniques are more suitable for brackish water.

2.2. Evaporative Techniques

Traditionally, evaporation techniques, especially MSF, have controlled the market of desalination techniques. Since 2004,, this trend has changed since reverse osmosis has proven to work properly and consume less energy. The question is still the final cost of the product, while preserving the environment. Evaporation techniques not only stand alone, but are now being considered as membrane evaporation techniques on the one hand and possibly a second stage for increasing recovery following RO desalination, approaching zero discharge. These trends still have long way to go before implementation.

2.2.1. Multi-Stage Flash

Multi-Stage Flash (MSF) distillation is based on condensing low-pressure steam as a heat source for the evaporation of seawater. It is still considered the simplest and most common technique in use. It has been in operation commercially for more than 60 years (Awerbuch, 1997). The technique is based on passing seawater through long, closed pipes passing through a series of flash chambers where hot seawater allows flashing along the bottom of the chambers. Vapor from the flash chambers heat the feed water flowing in the pipes. More heat is added in order to increase the temperature of the feed water to the initial high temperature, around 110^{o}C. This is done with the use of low-pressure steam, usually taken from a back-pressure turbine in a power station. The vapor condenses on the heating pipes and is pumped out as product. Usually, the concentrated brine is recycled with the feed to improve recovery ratio. Part of it is pumped out to sea.

2.2.2. Multi-Effect Distillation

Multi-stage evaporation comes from the chemical industry where water or solvent must be removed in order to concentrate a product in solution (Figure 1; McCabe et al., 2001). The evaporated liquid in the chemical industry is usually not the product, except for cases where the solvent is recovered from a certain reaction. The evaporation process consumes a great deal of energy. The need to save energy was the basis for the development of this multi-stage process, whereby more equipment (investment) is required in order to reduce the overall amount and cost of energy consumed. In most cases, the process involves 2-4 stages, sometimes called effects, and has been used for more than a century for solution concentration, crystallization, solution purification, etc. Since 1950, it has been used for seawater desalination, yet in the water industry it requires between 2-16 stages. Multi-Effect Distillation (MED) is more energy efficient than other evaporation techniques, including the Multi-Stage Flash system (Awerbuch, 1997). It is also considered to be more sophisticated. A low-temperature source of energy is used in most cases to feed the process. In most industrial cases, this is spent steam at a slightly elevated pressure exiting from a steam-operated power station, a source of heat that is available in refineries, or any low-level steam or hot fluid from other sources (Ophir & Lokiec, 2004).

The schematic of a horizontal tube Multi-Effect MED unit is presented in Figure 2 (IDE schematic view, old Internet publication). The steam enters the plant and is used to evaporate heated seawater. The secondary vapor produced is used to generate tertiary steam at a lower pressure. This operation is repeated along the plant from stage to stage. The primary steam condensate is returned to the boiler of the power station since it is of extremely high quality that is needed for turbine steam production. The MED technique is based on double-film heat transfer. Latent steam heat is transferred at each stage by steam condensation through the heat transfer surfaces to the evaporated falling film of seawater. The process is repeated up to 16 times or more in existing plants between the upper possible temperature and the lower possible cooling water, which depends on seawater temperature used for cooling the water. The product water is the condensate that accumulates from stage to stage. A vacuum pump/compressor is used to maintain the gradual pressure gradient inside the vessel by removing the accumulated non-condensable gases together with the remaining water vapor after the final condensation stage. The pressure gradient along the MED effects is dictated by the saturation pressure of the feed stream and the saturation pressure of the condensing steam exiting the last stage and is condensed by cooling with seawater. Typical pressure gradients of 5-50 kPa across the system (less than 5 kPa/stage) are typical.

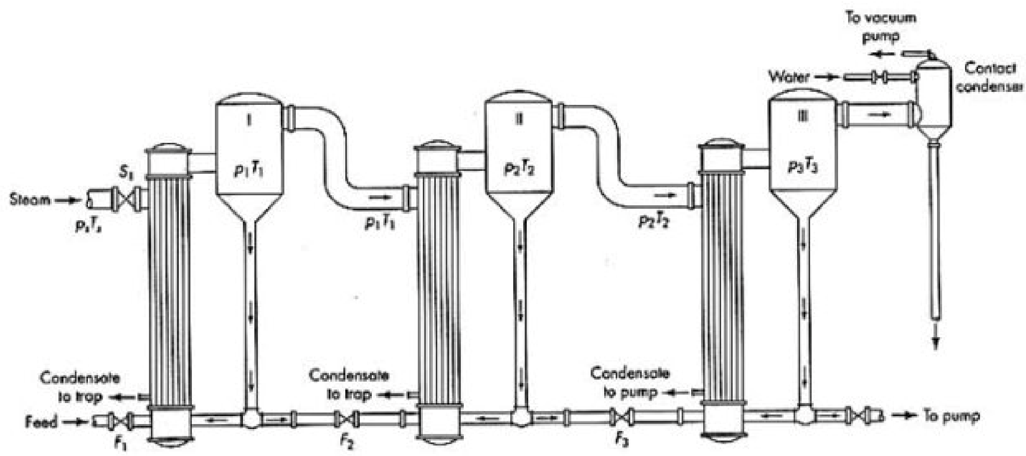

FIGURE 16.7
Triple-effect evaporator: I, II, III, first, second, and third effects; F_1, F_2, F_3, feed or liquor control valves; S_1, steam valve; p_s, p_1, p_2, p_3, pressures; T_s, T_1, T_2, T_3, temperatures.

Figure 1. Schematic view of industrial Multi-Effect evaporation (McCabe et al., 2001).

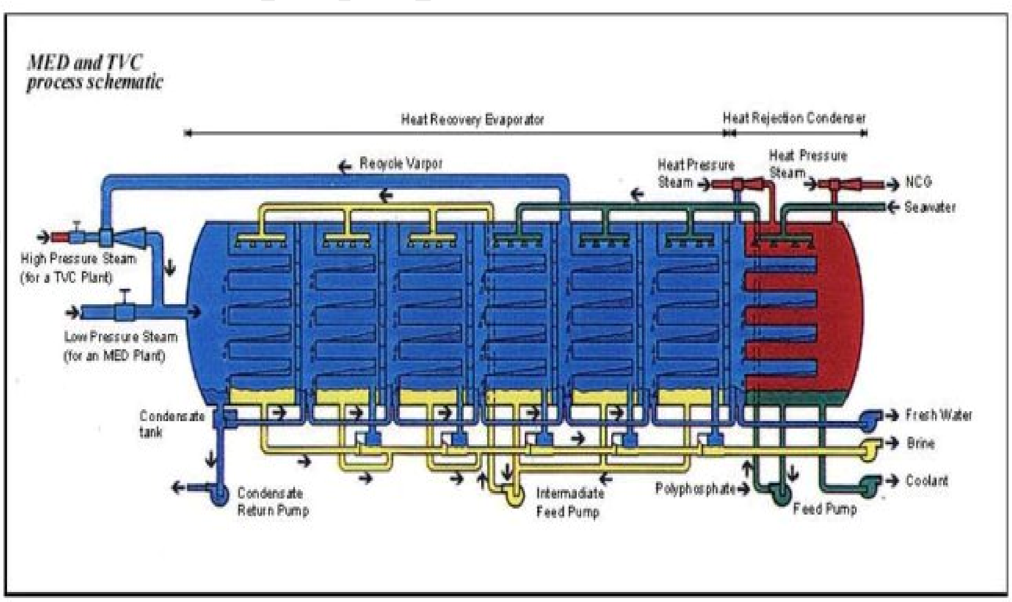

Figure 2. Schematic view of a horizontal tube Multi-Effect Distillation plant (IDE Design, Internet publication).

Steam condensation inside horizontal tubes and seawater evaporation on the outer side is the heart of one of the most common MED processes. Seawater is allowed to fall down a tube bundle. Heat transfer on both sides of the heat transfer area is considered highly efficient due to the low resistance of the thin falling films, which allows efficient operation with a low temperature difference across the tube walls. The low temperature difference is limited by the increasing boiling point elevation due to the increase in salt concentration while evaporating part of the water. It is also limited since at too high fluxes, the film starts to boil, nucleating bubbles, causing dry spots that may lead to salt precipitation. This, of course, should be avoided. The low temperature difference across the heat transfer surfaces allows designing a large number of effects between the steam temperature at the first stage and the temperature of the cooling seawater at the other side. More stages increase the performance ratio, or the GOR – Gain Output Ratio, which is actually the quantity of tons of water produced per ton of initial steam while reducing energy consumption of the process. The GOR in MED, which depends mainly on the initial steam temperature, can reach 15, which is higher than the maximum value of 10 for MSF. Therefore, energy/thermal efficiency is better for MED than it is for MSF (Ophir & Weinberg, 1997).

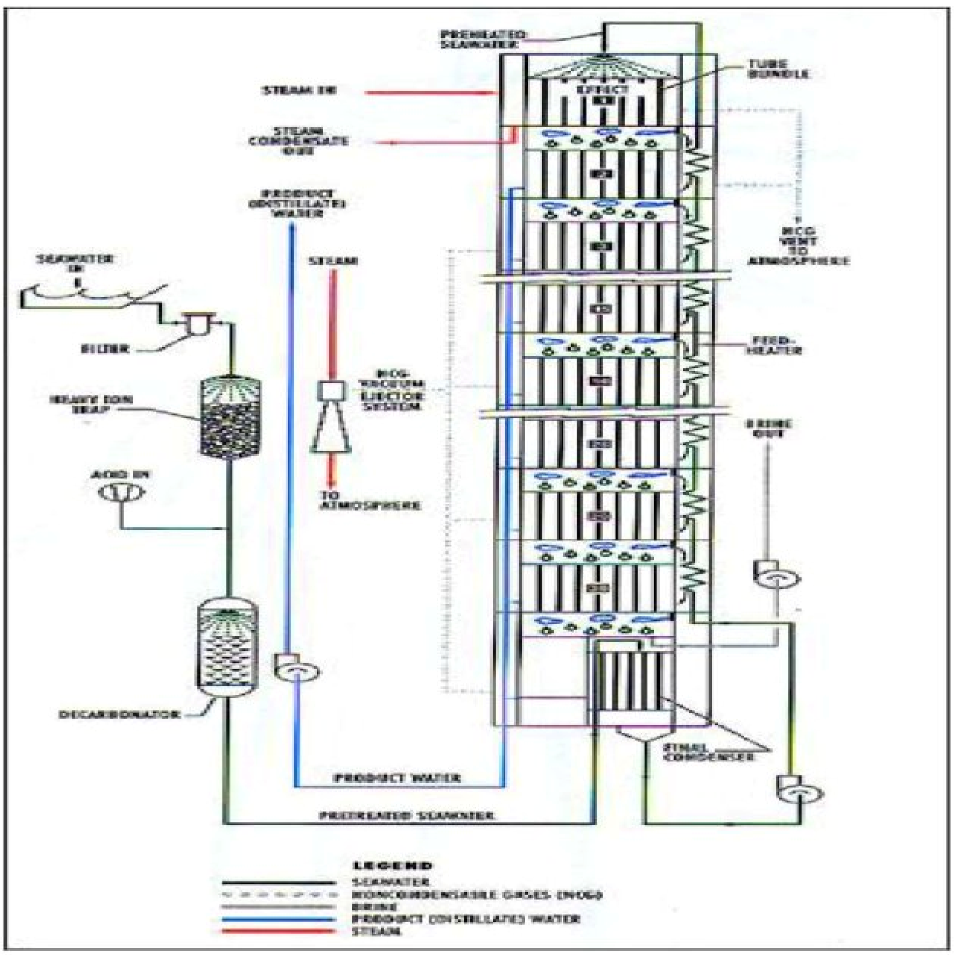

Figure 3. Schematic view of a vertical tube evaporator design (Pepp et al., 1997).

The economy of design and operation is dictated mainly by the availability of a source of low-cost energy. In this case, operational conditions may lead to the choice of low-cost materials and heat transfer surfaces when corrosion problems are minimized, while maintaining low probability of $CaSO_4$ precipitation on the tubes. Of course, the plant design cannot tolerate future changes in the cost of energy and materials.

The experience of IDE in MED plants has led to operation at low temperature differences across the heat transfer surfaces at good wetting of the surfaces in order to prevent scaling. Under these conditions, a plant can be operated below 70^{o}C using aluminum tubes, while operating below the saturation conditions of gypsum, involving up to 50% recovery. Corrosion rates are very low below this temperature, there is no need to remove oxygen, and cleaning is less frequent. Operating MED plants usually produce less than 30,000 m^3/day. Several trains of MED stages are built in parallel to each other to enable larger overall plant capacity.

Many possible MED system designs are available as horizontal or vertical tubes or flat-sheet heat exchangers during a stage. The stages may be arranged horizontally or vertically, and the seawater flow can be co-current or counter-current with the flow direction of the steam produced. These design variations affect water pumping in the system, which is related to part of the energy losses, and they affect the occasional cleaning of the heat exchangers. Specific process designs are sometimes developed for specific site conditions. Figure 3 illustrates a schematic view of a vertical tube evaporator design. Figure 4 shows a recent installation of four parallel 25,000m^3/day MED units in

Figure 4. Parallel IDE MED units, 4 x MED 25,000m^3/day Units, Tianjin, China.

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Biographical Sketch

Raphael Semiat is a professor in the Chemical Engineering Department, Technion, Israel Institute of Technology, Haifa, Israel. He holds the Yitzhak Rabin Memorial Chair in Science, engineering and management. He is the former director of the Grand Water research Institute and in charge of the Rabin Desalination Laboratory within the GWRI. He obtained his B.Sc. degree in Chemical Engineering from the Technion in 1973 and obtained his D.Sc. degree on MED Desalination in 1978 at the Technion. Expert in separation processes with industrial experience in IMI (TAMI), a subsidiary of Israel Chemicals Ltd, where he served as a senior research engineer and as the head of the Heat and Mass Transfer Engineering Research Department.

R. Semiat joined the Chemical Engineering Department, Technion, in 1990. His main research interests are: Process Development; Separation Processes with emphasis on Desalination. Of particular relevance are the research subjects associated with membranes processes and membrane fouling prevention. He has published over than hundred papers in scientific journals and similar number in conference proceedings. Most of his current research subjects are associated with the Israeli industry.

The GWRI's mission is to advance the science, technology, engineering and management of water, through inter-disciplinary research and development and dissemination of information, with emphasis on the water issues that face Israel. The GWRI is the Israel's leading institute of water research, closely linked with the water sector and industry.

The Rabin Desalination Laboratory, named in honor of the late Prime Minister of Israel, Yizthak Rabin, was founded in June 1996, as part of the Water Research Institute. The Rabin Desalination Laboratory is equipped with facilities for studying thermal and membrane separations (RO, NF, UF, MF and ED). Current projects include researches related to sea-water, brackish water desalination, sewage water recovery, drinking water quality etc. The laboratory has acquired special expertise in the field of scaling and fouling and their mitigation in both thermal and membrane processes.