MED DESALINATION- MODELLING, DESIGN AND OPTIMIZATION

Anwar O. Binamer
Kuwait Foundation for the Advancements of Sciences (KFAS), Research Directorate, Kuwait

Keywords: Multi-effect desalination, Adsorption desalination, Optimization, Thermal vapor compression, MED, MEDAD, ME-TVC, plate heat exchangers, exergy.

Contents

Summary

The new trend of combining conventional multi-effect distillation (MED) with multi-effect thermal vapor compression (ME-TVC) desalting units led to increase in single unit capacity of desalting system by more than fifteen times during a relatively short time period. The capacity of single unit using this technology currently reached 15 million imperial gallons per day (MIGD); one MIGD is 4550 m^3/day. A further step of development is expected in the near future by using a novel method of integration of conventional MED and adsorption cycle (AD).

This chapter gives an overview of MED desalination systems; types and classifications and presents the recent developments. These advances make this technology competing with the multi-stage flash (MSF) as well as seawater reverse osmosis (SWRO) desalination systems. The chapter discusses also new developments in the design, operation and material selection of ME-TVC units. A mathematical model of the ME-TVC desalination system is also presented in this chapter by using the Engineering Equation Solver (EES) Software. This model is used to evaluate and improve the performance of some new commercial ME-TVC units by using energy and exergy analysis. The results obtained from the presented model were compared with actual design data and showed good agreement. Another aim of this chapter is to develop a mathematical optimization model using the MATLAB program. This model is used to determine the optimum operating and design conditions of ME-TVC units of different numbers of effects to maximize the gain output ratio (GOR) of the units by using two optimization approaches: (1) Smart Exhaustive Search Method (SESM) and (2) Sequential Quadratic Programming (SQP).

1. Introduction

The multi-effect distillation (MED) process is one of the oldest methods used to desalt seawater (Safar and Al-Shammiri, 1999, Rahimi and Chua, 2017.). It has been used for industrial applications since the mid-nineteenth century. Several efforts were devoted to improve the evaporation process in different industries, and this led to better energy utilization (Shahzad et al, 2019).

In the desalination industry, the evaporation process takes place in a series of evaporators called effects. The principle of reducing the pressure in successive effects allows the feed seawater to boil at different temperatures without the need for additional heat after the first effect. The latent heat of condensation of the vapor generated in an effect is used as a heat source in the next effect (Khawaji et al, 2008). The vapor generated in the last effect condenses in the end condenser and the latent heat of condensation is rejected out of the system by the cooling water.

Although the multi-effect distillation (MED) process existed since the 1840s, the first on-land commercial venture of desalting plant using MED was in Kuwait. In 1950 the Kuwait Oil Company (KOC) commissioned a MED distillation plant of three-effect submerged tube evaporators to supply Kuwait City with 364 m^3/d of potable water. In 1953 the Ministry of Electricity and Water (MEW) commissioned its own first MED desalination plant in Shuwaikh comprising of 10 units of triple effect submerged tube evaporators each having a capacity of 455 m^3/d, a total capacity of 4550 m^3/d (i.e. about one Million Imperial Gallon per Day, MIGD), (MEW, 2019 and, Darwish et al, 2011). This plant was phased out due to scaling problems (GCC General Secretariat, 2014).

Year	Location	Country	Unit capacity	No. of units	Total capacity	GOR
2006	Al-Hidd	Bahrain	6 MIGD	10	60 MIGD	8.9
2007	Al-Jubail	KSA	6.5 MIGD	27	176 MIGD	9.8
2008	Fujairah	UAE	8.5 MIGD	12	100 MIGD	10
2009	Ras Laffan	Qatar	6.3 MIGD	10	63 MIGD	11.1
2012	Yanbu	KSA	15 MIGD	1	15 MIGD	9.7
2017	Az-Zour	Kuwait	10.8 MIGD	10	108 MIG	12

Table 1. Large MED-TVC projects in GCC countries

More improvements of the MED took place over the years and reached a stage at which many researchers expect that it will take a large share of the desalination market in the near future. Currently, the MED desalination system is widely used in the Gulf Cooperation Countries (GCC) and all over the world. Table1 shows that MED driven by thermal vapor compression (MED-TVC) projects are gaining more market shares in Bahrain, Saudi Arabia, UAE, Qatar and Kuwait with a total installed capacity of 60, 176, 100, 63 and 108 MIGD respectively.

2. The MED Classifications

The MED system can be classified according to the used type of evaporators, the feed seawater flow direction and the layout of the evaporators.

2.1. Types of Evaporators

Evaporators are the main part of any thermal desalination process. An evaporator is a heat exchanger, where heating steam condenses on one side while vapor is generated on the other side.

The evaporators can be classified as follows:
(a) Submerged tube evaporator, (b) Vertical tube falling film evaporator, (c) Horizontal falling film evaporator and (d) Plate heat exchanger evaporator (El-Dessouky and Ettouney, 2002)

(a) Submerged tube evaporator

In submerged tube evaporators, heating steam flows inside bundles of tubes submerged in seawater and contained in a shell as shown in Figure 1. The heating steam (S) loses its latent heat and condenses before it flows out of the tube bundles (S_c). The water surrounding the submerged tube bundles starts evaporation as it gains the latent heat of the steam condensed in the tubes. The main disadvantage of submerged tube evaporators are the high rate of scale formation due to limited movement of the saline boiling water at the outer surface of the tubes and the low heat transfer coefficient (Darwish et al 2006). This type of evaporators was the most commonly used in the first half of the twentieth century (El-Dessouky and Ettouney, 2002). Many MED units using this type of evaporators were phased out after five years of operation in the late 1950s in Kuwait, Qatar and Kingdom of Saudi Arabia (KSA) due to scaling problems and high operation and maintenance costs (GCC General Secretariat, 2014). It was reported that the cleaning time was equal to or more than the actual production time (El-Dessouky and Ettouney, 2002).

(b) Vertical tube falling film evaporator (VTE)

In vertical tube evaporators (VTE), seawater is fed to the inside top of the tubes and flows down by gravity along-side the tube walls as a thin film. Meanwhile the heating steam is flowing and condenses outside the tubes which are contained in a shell (Glover, 2004). Evaporation takes place in the vertical thin film of the feed seawater flowing inside the tubes while heating steam condenses at the outer surface of the tubes. Heat is transferred from outside to the inside heat transfer area of the tubes as shown in Figure 2. The simultaneous condensation and boiling on the tube sides gives a high heat transfer rate (Darwish et al 2006). Additionally, corrugated and double fluted tubes are also used in these evaporators for further heat transfer enhancement (Belessiotis et al, 2016). On the other hand, distributors of different configurations are used on the top of the tube to ensure proper falling film distribution of seawater inside the tubes, such as perforated plates, spray nozzles and weirs. (Husain et al, 2010). A main drawback of VTE is the complexity of design and operation compared to horizontal falling film evaporator (El-Dessouky and Ettouney, 2002). It is difficult to stack VTEs above each other with a reasonable height because the height of an effect would be close to 5 m, which limits the number of effects to a small number (Darwish et al, 2006). Generally, this type is preferable in the concentration of dairy products and other sugar solutions and not suited for salting or scaling materials (Glover, 2004).

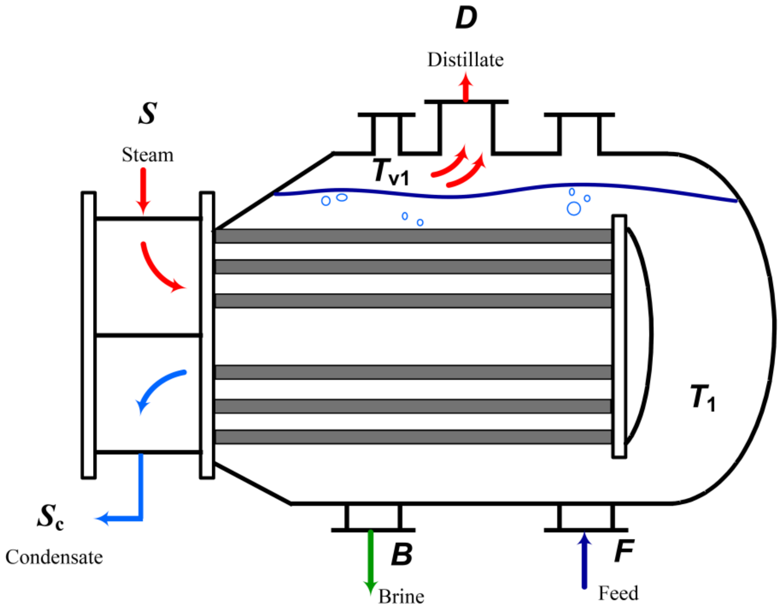

Figure 1. Submerged tube evaporator

(c) Horizontal tube falling film evaporator (HFFE)

Horizontal tube falling film evaporators (HFFE) are the most commonly used type in the MED (El-Dessouky and Ettouney, 2002; Legorreta et al, 1999; Belessiotis et al 2016). In HFFE, feed seawater is distributed as a thin film on the outer surface of horizontal tube bundles, while the heating steam flows and condenses on the inside of the tube bundles as shown in Figure 3. The tubes are arranged in several rows with square or rectangular layout to simplify the cleaning process of the outside tubes surface (El-Dessouky and Ettouney, 2002). All modern mechanical or thermal vapor compression systems with multiple effects are utilizing the HFFE type because of the following:

- Higher heat transfer coefficients due to the use of multiple tube passes of the heating steam compared to the single pass in the vertical tube evaporators (Shahzad et al, 2018).
- Stability and simplicity in operation and maintenance, and less scaling problems compared with vertical tube evaporators.

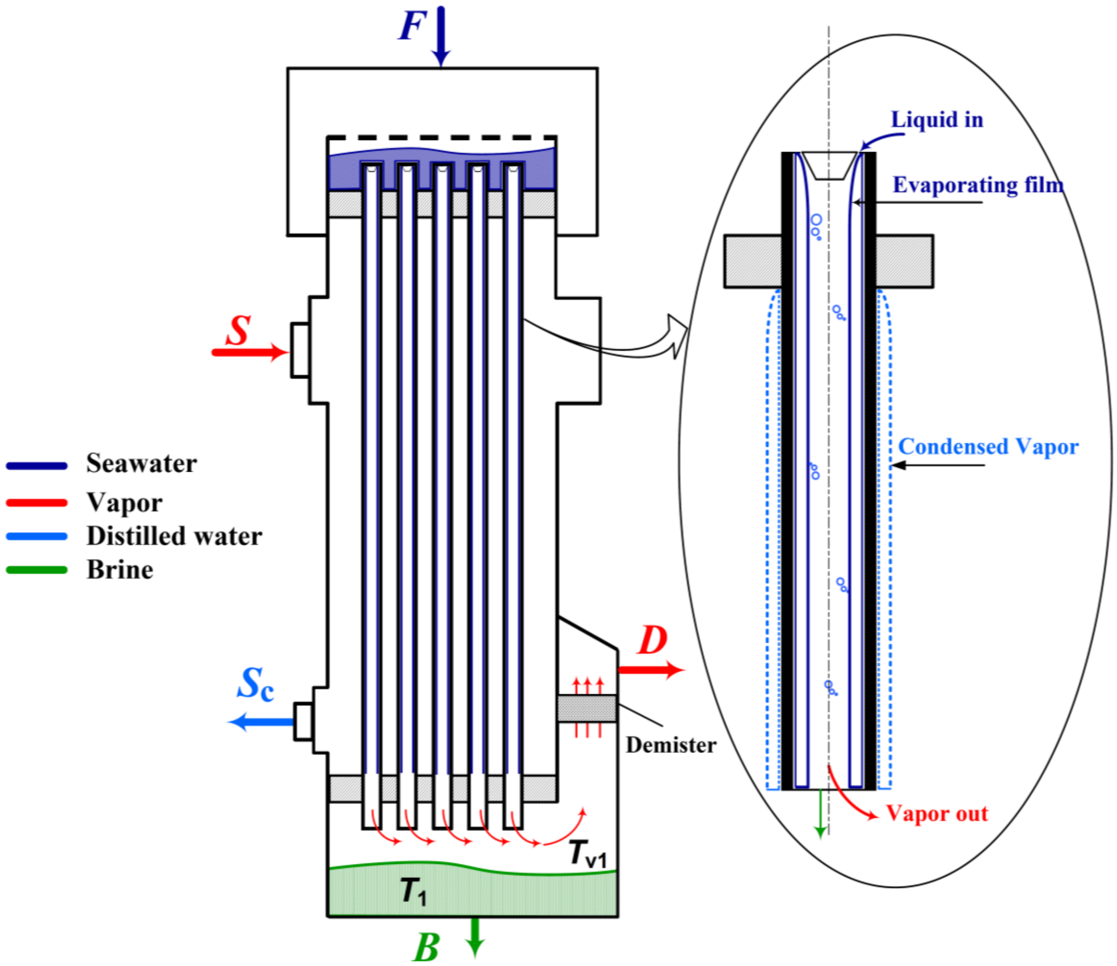

Figure 2. Vertical tube falling film evaporator

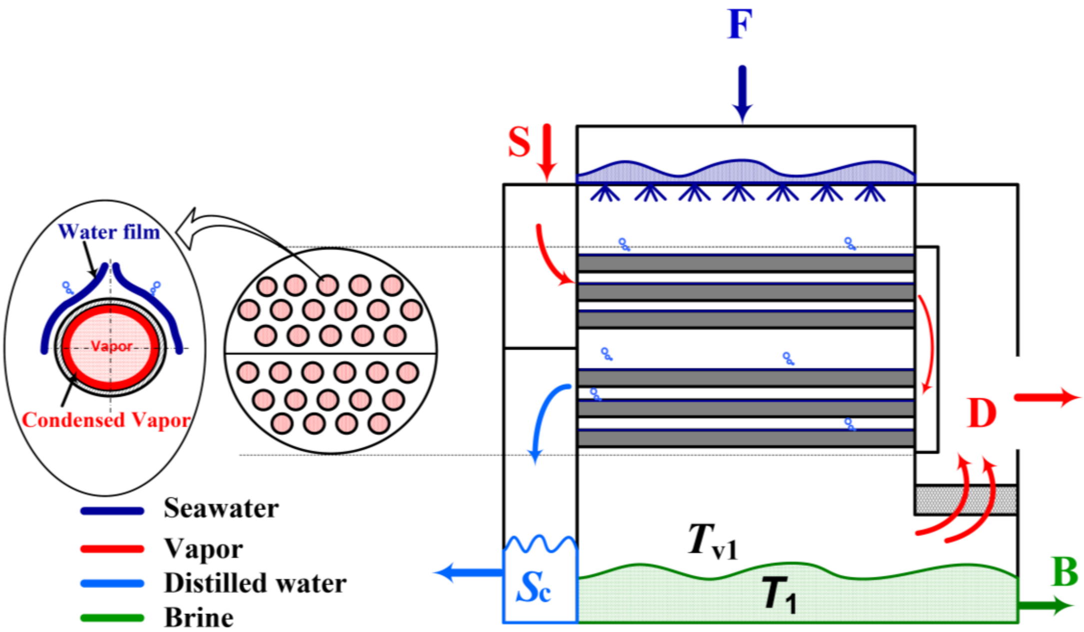

Figure 3. Horizontal tube falling film evaporator

(d) Plate heat exchanger evaporator, PHE

A plate heat exchanger (PHE) evaporator is a compact type of plate heat exchanger that uses a series of thin plates to transfer heat between two fluids (Fábio et al, 2015). The PHE evaporators are adopted by few manufactures as an alternative of conventional shell and tube evaporators in the last few decades. The main advantages of PHE evaporators compared to the conventional shell and tube evaporators are: (Wang et al, 1999; Legorreta et al, 1999; Fábio et al, 2015)

– Highly effective, i.e. high heat transfer coefficients, since the fluids are exposed to a much larger surface area spreading out over the plates.
– Highly compacted: i.e. high heat transfer surface area to volume ratio gives smaller space requirement and weight.
– Highly flexible: i.e. more or less heat is transferred by adding or removing plates respectively and an evaporator can also be easily disassembled for inspection and cleaning.

Alfa Laval Company, a leading manufacturer using this technology, provides a wide range of evaporators for a variety of applications and capacities (Legorreta et al, 1999). Each application depends on the desired product which can be either the vapor or the concentrated stream or both. (Glover, 2004).

Figure 4 shows the working principle of one of Alfa Laval PHE evaporators that is used in the beet sugar industry and in many other applications (www.Alfalaval.com).

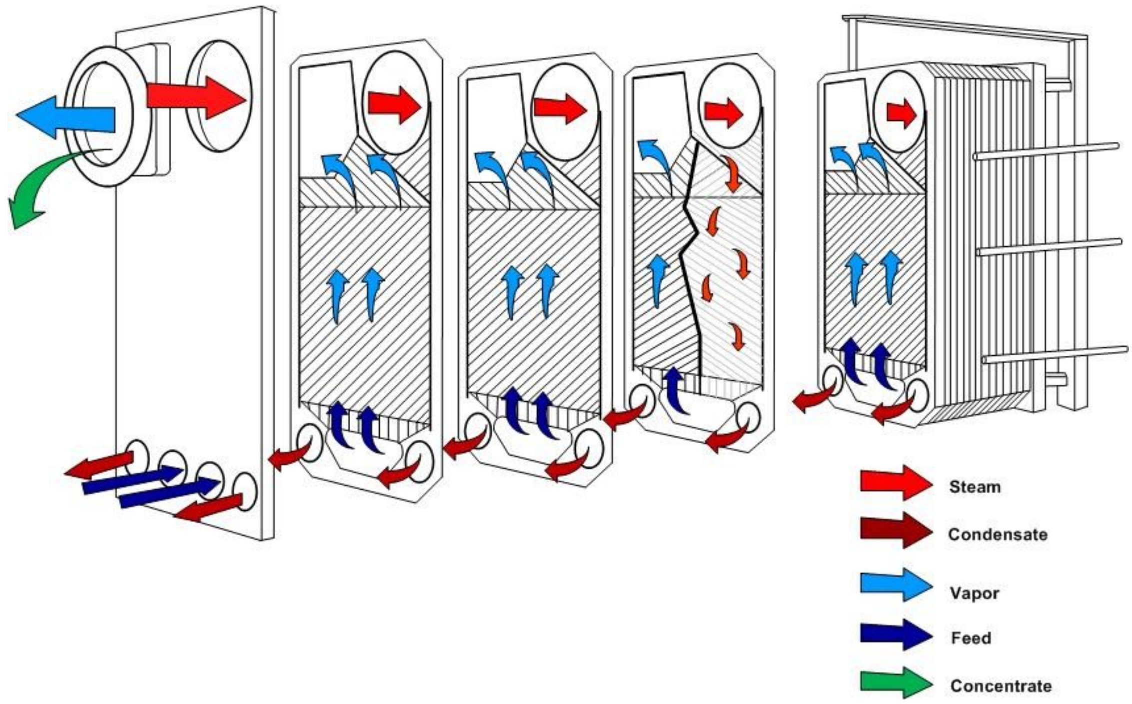

Figure 4. Plate evaporator (Alfa Laval)

Alfa Laval designed a special PHE evaporator for desalination, which can be used for a two-phase flow on both sides of the plate, one for evaporation, and one for condensation (Legorreta et al, 1999). The application of PHE evaporators in MED will be discussed later in detail in a separate section.

2.2. Feed Water Flow Direction

MED can be classified according to feed water flow direction to the evaporators into three main schemes; forward, backward and parallel feed arrangement (Darwish and Abdulrahim, 2008). These three arrangements differ in the flow directions of both the vapor formed as well as the feed and the brine streams (El-Dessouky and Ettouney, 2002).

(a) Forward Feed Arrangement.

The forward feed arrangement is not widely used for desalination on industrial scale applications because of the layout complexity (El-Dessouky and Ettouney, 2002). In this type the feed seawater F is supplied to the first effect (of the highest temperature) directly after leaving the bottom condenser at a feed temperature of T_f. The vapor formed in the first effect is directed to provide heat the second effect; and the brine in the first effect is cascaded to the second effect as a feed and so on up to the last effect. So, both the feed and vapor entering the effects have the same direction. Figure 5 shows the layout of this arrangement with four effects along with its temperature distribution. The main feature of this arrangement is the ability to operate at high top brine temperature (TBT) with less scale formation problem compared to the backward feed arrangement. It also needs less pumping energy compared to the backward feed arrangement. The main drawbacks of the forward feed are the high energy (heat) needed to heat all the feed water from T_f to the TBT, and the required high heat transfer area in the first effect compared with others.

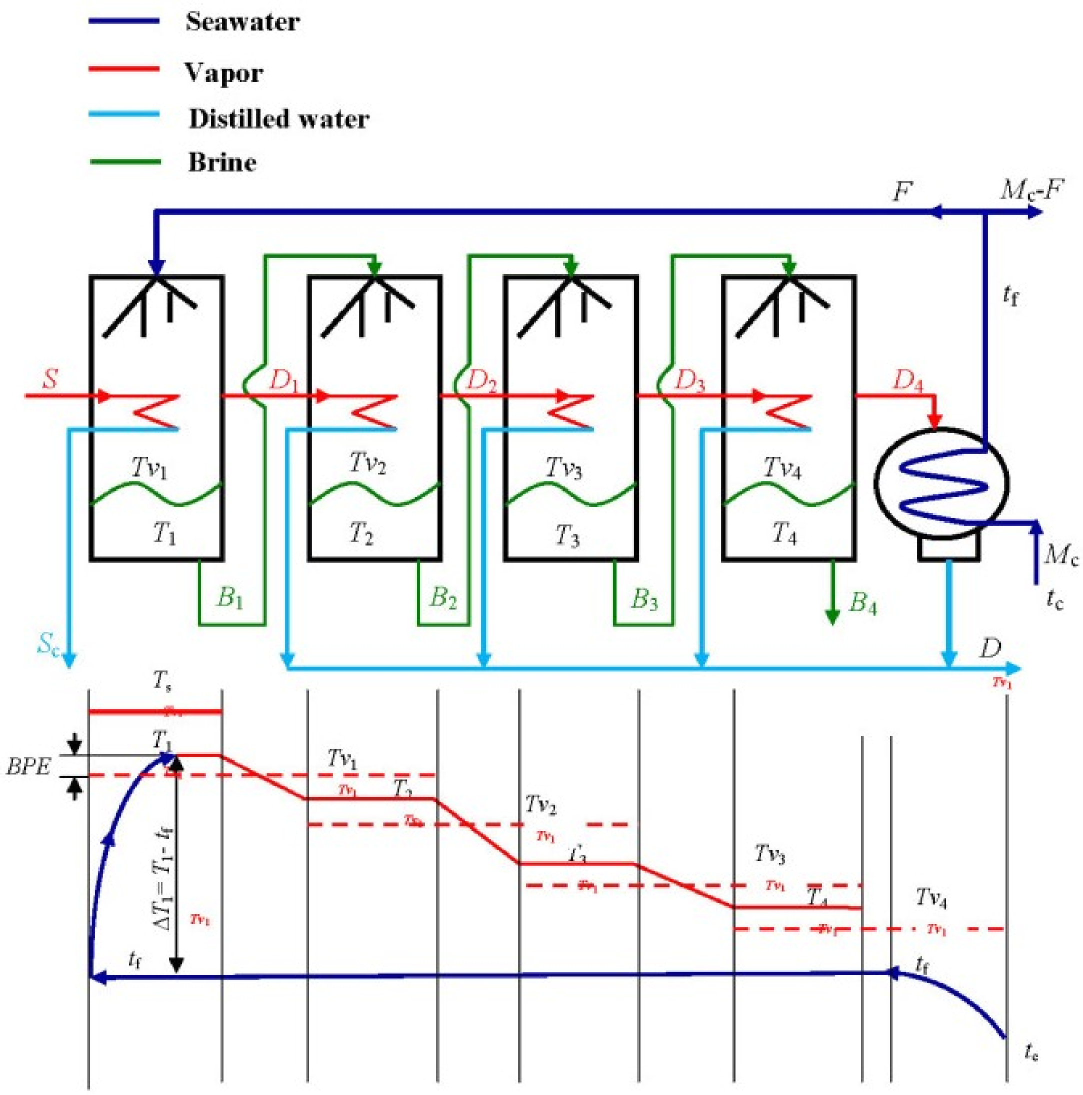

Figure 5. Forward feed arrangement with four effects and its temperature distribution.

(b) Backward feed arrangement

A backward feed arrangement with four effects is shown in Figure 6. The feed seawater F at temperature T_f is directed to the last (fourth) effect, the lowest temperature effect. The brine leaving the fourth effect is directed to the third effect as a feed and so on until it reaches the first effect. The brine leaving the first effect is blown down to the sea. This means that the feed and vapor flows in the effects have opposite directions. The main feature of the backward feed system is its higher performance ratio compared to the forward feed arrangement, because less energy is needed to heat the feed seawater to the TBT. Another feature is that the heat transfer area required is almost uniformly equal for all effects. The main drawbacks of the backward feed are: 1) the first effect has the highest temperature and highest salt concentration which gives high scale formation tendency and requires more maintenance, and 2) high pumping energy since pumping is needed to move the brine from lower temperature and pressure effects to those at higher temperatures and pressures.

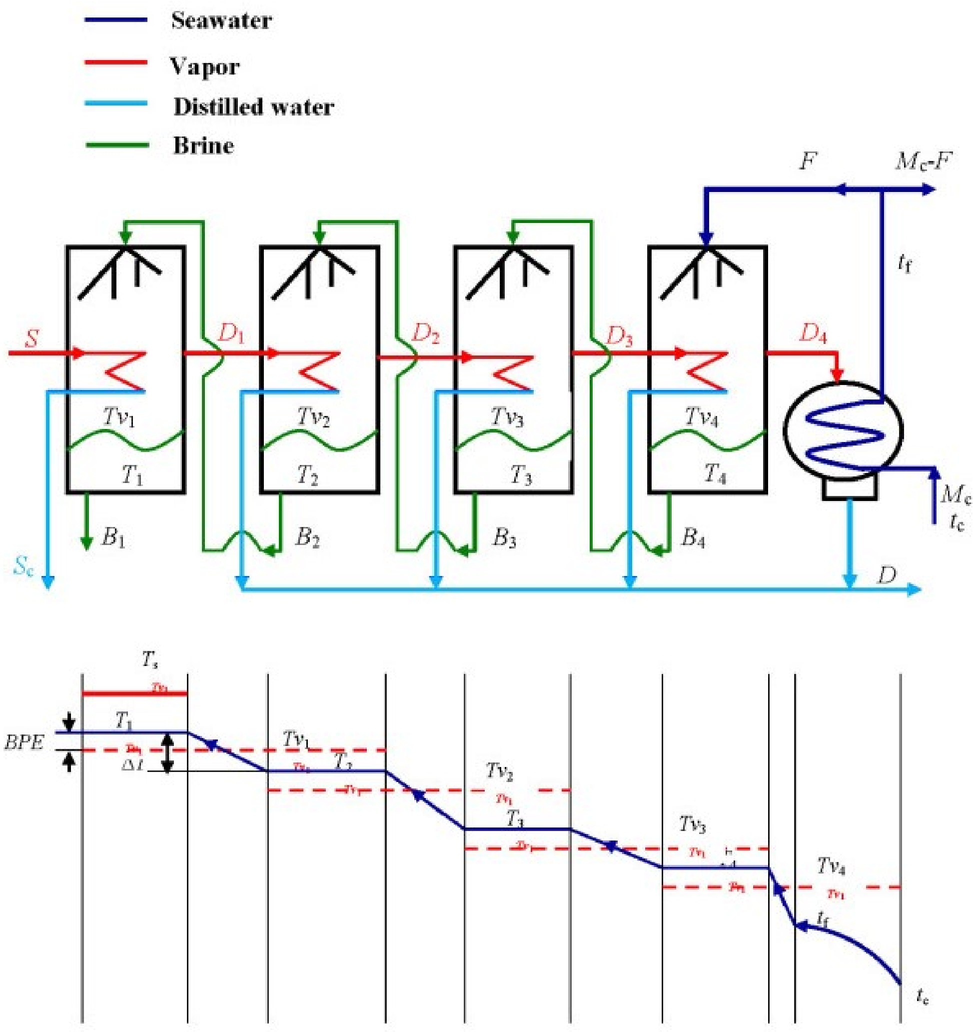

Figure 6. Backward feed arrangement with four effects and its temperature distribution.

(c) Parallel feed arrangement

A parallel feed arrangement with four effects is shown in Figure 7 with its temperature distribution. In this configuration, the feed seawater is divided and distributed equally among all effects (which is equal to $F/4$ here). So, the amount of feed and its salinity and temperature in each effect are the same. The main features of this arrangement are: 1) High performance ratio due to less energy needed to heat the feed in each effect ($F/4$) from T_f to the effect evaporation temperature, 2) Simplicity of design, construction and operation compared to the other two feed arrangements. The main drawback is that it may require brine recirculation within the effect to ensure adequate wetting of the heat transfer surfaces since the feed is divided equally between all the effects, feed into each being ($F/4$).

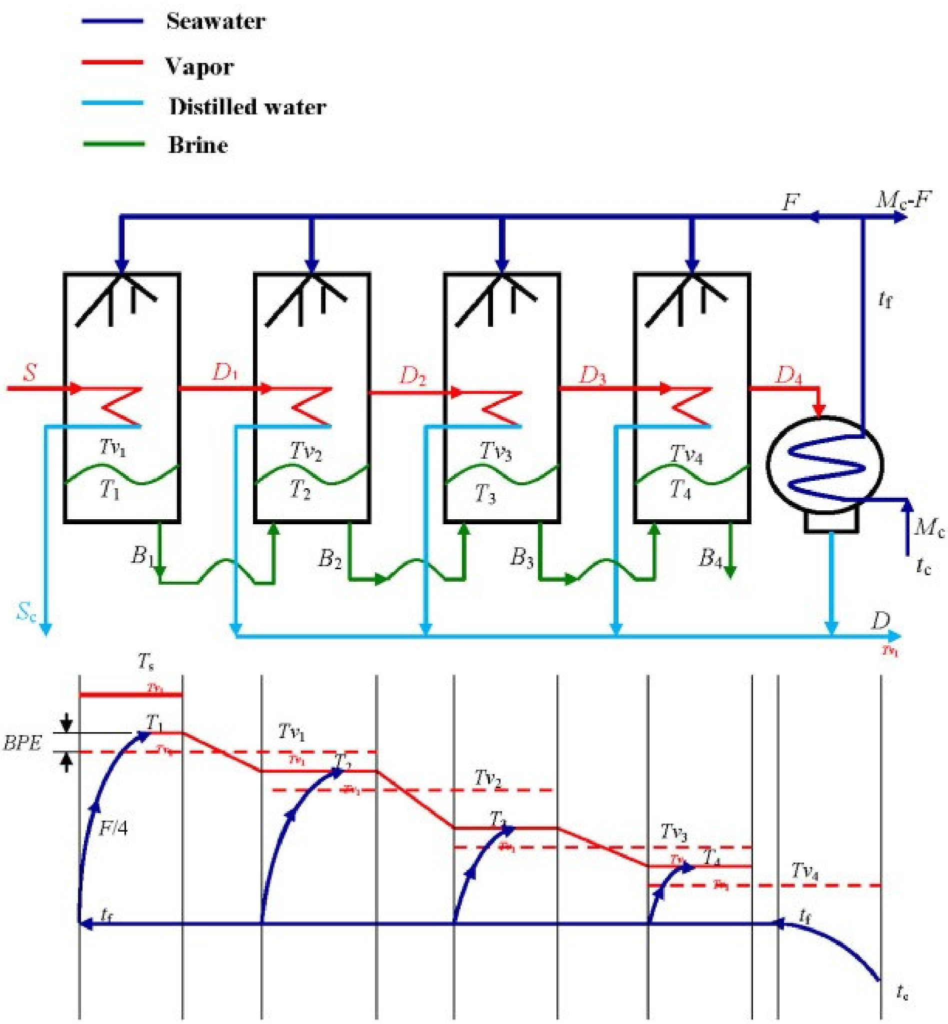

Figure 7. Parallel feed arrangement with four effects and its temperature distribution.

So, the parallel feed arrangement is widely used in desalination plants. A modified version of this arrangement is shown in Figure 8, where several regenerative feed heaters are also used to heat the feed water progressively before entering the first effect.

Also, combinations of parallel/forward feed or parallel/backward feed can be found in large capacity desalination plants that have large number of effects; e.g., more than four effects.

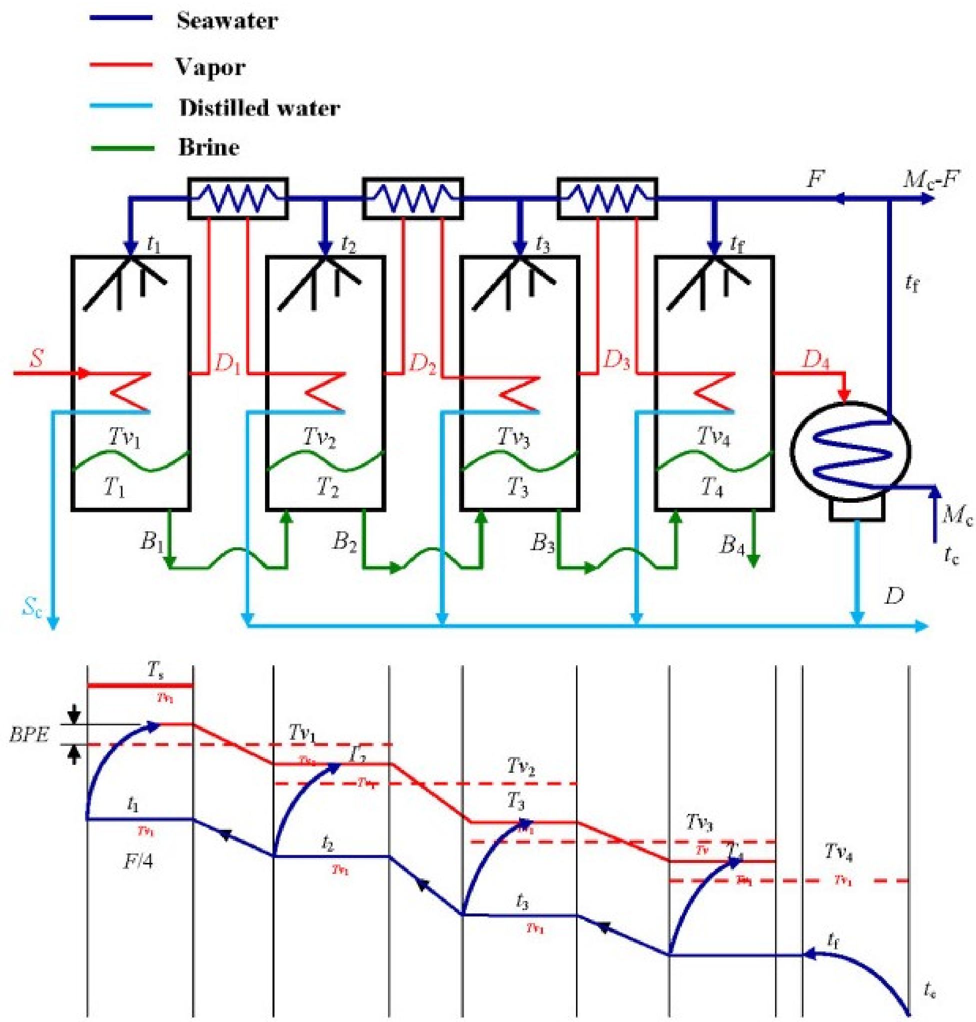

Figure 8. Parallel feed arrangement with regenerative feed heaters

-

-

-

TO ACCESS ALL THE **76 PAGES** OF THIS CHAPTER,
Visit: http://www.eolss.net/Eolss-sampleAllChapter.aspx

Bibliography

Abdulrahim H. K., Al-Rasheed A. M., Hassan A.S., Mabrouk A. A., Shomar B., Darwish M.A. (2017). Reverse osmosis desalination system and algal blooms Part III: SWRO pretreatment. *Desalination and water treatment*. Taylor and Francis. 60 (2017) 11–38. [This paper reviews the available pretreatment methods for SWRO desalination, and their effectiveness in enhancing the removal of harmful algal blooms].

Alasfour, F.; Darwish, M. and Bin Amer, A. (2005). Thermal analysis of ME- TVC + MEE desalination system. *Desalination*, Elsevier. Vol. 174 (2005) 39-61.

Alfa Laval. Evaporators and condensers in a new dimension. The complete range. Available at https://www.alfalaval.com/globalassets/documents/products/process-solutions/thermal-solutions/evaporators-and-condensers-in-a-new-dimension_pfl00094.pdf

Alfa Laval. Fresh water for life Desalination solutions for every need. Available at https://www.alfalaval.gr/globalassets/documents/products/process-solutions/desalination-solutions/multi-effect-desalination/fresh-water-brochure-pee00251en-1201.pdf

Alfa Laval. Reference List 2012. Examples of Desalination unit installations. Available at https://www.alfalaval.in/globalassets/documents/products/process-solutions/desalination-solutions/multi-effect-desalination/reference-list-2012-05-desalination-units-dksosrbver02.pdf

AL-Habshi, S. (2002). Simulation and economic study of the MED-TVC units at Umm Al-Nar desalination plant. Thesis report, (2002) UAE.

Al-Juwayhel, F.; El-Dessouky, H. and Ettouney, H. (1997). Analysis of single-effect evaporator desalination systems combined with vapor compression heat pumps. *Desalination*, Elsevier. Vol. 114 (1997) 253-275.

Almutairi, A.; Pilidis, P.; Al-Mutawa, N.; Al-Weshahi, M. (2017) Exergetic and Sustainability Analysis of an Intercooled Gas Turbine Cogeneration Plant with Reverse Osmosis Desalination System. J. Energy Eng. **2017**

Al-Najem, N.; Darwish, M. and Youssef, F. (1997). Thermo-vapor compression desalination: energy and availability analysis of single and multi-effect systems. *Desalination*, Elsevier. Vol. 110 (1997) 223 – 238.

Al-Shammiri M., Safar M. (1999). Multi-effect distillation plants: state of the art. *Desalination*, Elsevier. Vol. 126 (1999) 45-59. [This paper discusses the technical features of different commercial MED plants in addition to their operation and maintenance, and associated problems].

Ashour, M. (2002) Steady state analysis of the Tripoli West LT-HT-MED plant. *Desalination*, Elsevier.Vol. 152 (2002) 191-194.

Bejan, A.; Michael, J. and George, T. (1996). *Thermal design and optimization*, John Wiley and Sons, 0471584673, New York, 1st edition.

Belessiotis V., Kalogirou S. and Delyannis E. (2016). Indirect Solar Desalination (MSF, MED, MVC, TVC) *Thermal Solar Desalination: Methods and Systems*. Academic press, Elsevier. 283-326. [This book presents several thermal seawater desalination technologies All types of solar thermal desalination technologies are also presented].

Bin Amer, A. (2009). Development and optimization of ME-TVC desalination system. *Desalination*, Elsevier. Vol. 249 (2009) 1315-1331.

Bin Amer, A. (February 28th, 2011). New Trend in the Development of ME-TVC Desalination System, *Desalination, Trends and Technologies*, Michael Schorr, IntechOpen, UK. 185-214.

Björn Palm and Joachim Claesson (2006) Plate Heat Exchangers: Calculation Methods for Single and Two-Phase Flow, *Heat Transfer Engineering*, Taylor and Francis. 27:4, 88-98a

Choi, H.; Lee, T.; Kim, Y. and Song, S. (2005). Performance improvement of multiple-effect distiller with thermal vapor compression system by exergy analysis. *Desalination*, Elsevier. Vol. 182 (2005) 239-249.

Cipollina, A.; Micale, G. and Rizzuit, L. (2005). A critical assessment of desalination operation in Sicily. *Desalination,* Elsevier. Vol. 182 (2005) 1-12.

Darwish M. A. (2015). *Desalination Engineering*. Balaban Desalination Publications; 1st edition (September 1, 2015). [This book covers the basic of thermal desalination processes. Case studies of cogeneration power desalting plants are also presented].

Darwish M. A., Abdulrahim H. K. (2007). Feed water arrangements in a multi-effect desalting system. *Desalination*, Elsevier. Vol. 228 (2008), 30-54. [This paper outlines thermodynamic analysis of the different feed water arrangements in multi-effect desalting systems].

Darwish M. A., Al-Juwayhel F., Abdulraheim H. K (2006). Multi-effect boiling systems from an energy viewpoint. *Desalination*, Elsevier. Vol. 194 (2006) 22–39. [This paper presents different terms used to evaluate the efficiency of thermal desalting systems in order to evaluate the real performance of the MED].

Darwish, M. A. and Alsairafi, A. (2004). Technical comparison between TVC/MEB and MSF. *Desalination*, Elsevier. Vol. 170 (2004) 223-239. [This paper compares between typical MSF and MED units, their size, consumed energy, performance, and factors affecting the choice].

Darwish, M. A. and El-Hadik, A. A. The Multi-Effect Boiling Desalting System and its Comparison with the Multi-Stage Flash System 1986. *Desalination*, Elsevier. Vol. 60, 251-265.

Darwish, M. A.; Alasfour, F. and Al-Najem, N. (2002). Energy consumption in equivalent work by different desalting methods case study for Kuwait. *Desalination*, Elsevier. Vol. 152 (2000) 83-92.

Darwish, M. A; Darwish, Ali; Darwish, Amina. (2011). Fifty years of MSF desalination in Kuwait and sustainability issues. *Desalination and water treatment*. Taylor and Francis, Vol. 29, 1-3, 343-354. [This paper provides the history of developing MSF desalination units in Kuwait].

Demir H., Mobedi M., Ülkü S. (2008). A review on adsorption heat pump: Problems and solutions. *Renewable and Sustainable Energy Reviews*. Elsevier. 12 (2008) 2381-2403.

El-Dessouky, H. and Ettouney, H. (1999). Multiple-effect evaporation desalination systems: thermal analysis. *Desalination*, Elsevier. Vol. 125 (1999) 259-276.

El-Dessouky, H. and Ettouney, H. (2002). *Fundamental of salt-water desalination*, Elsevier Science, 1st edition. [This book focuses on different desalination processes used in industry. It includes a large number of solved examples and case studies].

El-Dessouky, H.; Ettouney, H. and Al-Juwayhel, F. (2000). Multiple effect evaporation- vapor compression desalination processes. *Trans IChemE*, Vol. 78, Part a, (May 2000) 662-676.

Fábio A.S. Mota, E.P. Carvalho and Mauro A.S.S. Ravagnani. (July 29th 2015). Modeling and Design of Plate Heat Exchanger. *Heat Transfer Studies and Applications*. Salim Newaz Kazi (IntechOpen),165-199.

Fisher, U.; Aviram, A. and Gendel, A. (1985). Ashdod multi-effect low temperature desalination plant report on year of operation. *Desalination,* Elsevier. Vol. 55 (1985) 13-32.

Glover W. B. (2004). Selecting evaporators for process applications. Heat Transfer. *Chemical Engineering Progress* (CEP). AIChE. December 2004, 26-33.

Hamed, O.; Zamamiri, A.; Aly, S. and lior, N. (1996). Thermal performance and exergy analysis of a thermal vapor compression desalination system. *Energy Conversion and Mgmt*, Elsevier. Vol. 37 (1996) 379-387.

https://www.kaust.edu.sa/en/news/solar-desalination%E2%80%94from-lab-to-plant

Husain A., Al Radif A., El Nashar A., Borsani R., Bushara M. (2010). Some practical aspects of desalination processes. *Physical, chemical and biological aspects of water.* Volume I. Desalination and water resources. Encyclopedia of Life Support Systems (EOLSS). 168-209.

Ihsan Ullah and Rasul. M. G. (2019). Recent Developments in Solar Thermal Desalination Technologies: A Review. MDPI. *Energies* 2019, 12, 119.

Irvine Thomas F., Peter E. Liley. (1984). *Steam and Gas Tables with Computer equations*. Academic Press, INC. Harcourt Brace Jovanovich Publishers. 1st edition.

Khawaji A. Kutubkhanah I. Wie J. (2008). Advances in seawater desalination technologies. *Desalination*, Elsevier. Vol. 221, Issues 1–3, 2008, 47-69. [This paper reviews the status, practices, and advances in desalination technologies, provides an overview of RandD activities and outlines the future prospects].

Legorreta C., Hinge S., Tonner J., Lovato A. (1999). Plates — the next breakthrough in desalination. *Desalination*, Elsevier. Vol. 122 (1999), 235-246.

Michels, T. (1993). Recent achievements of low temperature multiple effect desalination in the western areas of Abu Dhabi, UAE. *Desalination*, Elsevier. Vol. 93 (1993) 111-118.

Michels, T. The modern MED pursuing its way in the Gulf Region. *European Desalination Society, Newsletter,* 11 January 2001.

Mitra S., K. Srinivasan, P. Kumar, S. S. Murthy, P. Dutta. (2014). Solar driven adsorption desalination system. *Energy Procedia*, Elsevier. Vol. 49 (2014) 2261-2269.

Ng Kim C. Solar desalination — from lab to plant. KAUST (News). 2018. Available at

Ng Kim C., Thu K., Kim Y., Chakraborty A., Amy G. (2013). Adsorption desalination: An emerging low-cost thermal desalination method. *Desalination*, Elsevier. Vol. 308 (2013) 161-179.[This paper presents an experiments of 3-stage MED and MEDAD plants. These plants have been tested at assorted heat source temperatures ranging from 15°C to 70°C].

Ng Kim C., Thu K., Oh S. J., Ang L., Shahzad M. W., Bin Ismail A. (2015). Recent developments in thermally-driven seawater desalination: Energy efficiency improvement by hybridization of the MED and AD cycles. *Desalination*, Elsevier. Vol. 356 (2015) 225-275. [This paper discusses the aspects of AD and related hybrid MEDAD cycles, at theoretical models and experimental pilots].

Ng Kim C., Thu K., Shahzad M. W., Chun W. (2014). Progress of adsorption cycle and its hybrids with conventional multi-effect desalination process. *IDA Journal of Desalination and Water Reuse,* Taylor and Francis. Vol. 6. 44-56.

Olsson, J. and Snis, M. (2007). Duplex- A new generation of stainless steel for desalination plants. *Desalination*, Elsevier. Vol. 205, Issues 1-3 (2007) 104-113. [This paper describes the technical terms of duplex stainless steels in both membrane and distillation processes].

Ophir, A. and Lokiec, F. (2005). Advanced MED process for most economical sea water desalination. *Desalination,* Elsevier. Vol. 182 (2005) 187-198. [This paper describes the design principles and energy considerations of MED plants. It provides an overview of various cases of waste heat utilization, and cogeneration MED plants].

Palenzuela P., Alarcón-Padilla D., Zaragoza G. (2015). *Concentrating Solar Power and Desalination Plants: Engineering and Economics of Coupling Multi-Effect Distillation and Solar Plants.* Springer. Switzerland, 1st edition. [This book provides a detailed examination of coupling Concentrating Solar Power and Desalination plants].

Peterson P. F., Zhao H. (2006). An optimized system for Advanced Multi-Effect Distillation (AMED) using waste heat from closed gas Brayton Cycles. U.C. Berkeley. Report UCBTH-05-003.

Peultier, J.; Baudu, V.; Boillot, P. and Gagnepain, J. (2009). New trends in selection of metallic material for desalination industry. *Proceeding of IDA world congress on desalination and water reuse*. Dubai, November 2009, UAE.

Power, R. (1994). *Steam Jet Ejectors for the Process Industries*, McGraw-Hill, 0070506183, NewYork.

Rahimi B. Chua H. T. (2017). *Low grade heat driven multi-effect distillation and desalination*. Elsevier. 1st edition. [This book describes the development of advanced MED technologies driven by low grade sensible heat in remote areas].

Reddy, K. and Ghaffour, N. (2007). Overview of the cost of desalinated water and costing methodologies. *Desalination*, Elsevier. Vol. 205 (2007) 340-353.

Rodriguez L. G., Padilla D. 2007. Application of absorption heat pumps to multi-effect distillation: A case study of solar desalination. *Desalination*, Elsevier. Vol. 212 (2007) 294-302. [This paper points out different advantages of coupling an absorption heat pump to a MED system to increase the competitiveness of both conventional and solar powered MED plants]

Saeed M. O., Al-Nomazi M. A., Al-Amoudi A. S. (2019). Evaluating suitability of source water for a proposed SWRO plant location. *Heliyon*, Elsevier. (5) 2019. eo1119.

Sayyaadi, H and Saffaria, A. (2010). Thermo-economic optimization of multi-effect distillation desalination systems. *Applied Energy*, Elsevier. Vol. 87 (2010) 1122-1133.

Shahzad M. W, Burhan M, Ng Kim C. (2018) Development of Falling Film Heat Transfer Coefficient for Industrial Chemical Processes Evaporator Design. Statistical Approaches with Emphasis on Design of Experiments Applied to Chemical Processes. Valter Silva, IntechOpen, 115-136.

Shahzad M. W., Burhan M., Ybyraiymkul D. and Choon Ng K. (2019). Desalination Processes' Efficiency and Future Roadmap, *Entropy*. MDPI. 2019, 21, 84.

Shahzad M. W., Ng Kim C., Thu K., Saha B. B., Chun W. G. (2014). Multi-effect desalination and adsorption desalination (MEDAD): A hybrid desalination method. *Applied Thermal Engineering*, Elsevier. Vol. 72 (2014) 289-297.

Shahzad M. W., Thu K., Kim Y., Ng Kim C. (2015). An experimental investigation on MEDAD hybrid desalination cycle. *Applied energy.* Elsevier. Vol. 148 (2015). 273-281.

Shahzad M. W., Thu K., Li A. Bin Ismail A., Ng Kim C. (2015). Adsorption Cycle and Its Hybrid with Multi-Effect Desalination. Desalination Updates. Robert Ning. (IntechOpen). 185-213.

Sharqawy M.H., J.H. Lienhard V, S.M Zubair, (2010) "Thermophysical Properties of Sea Water: A Review of Existing Correlations and Data," *Desalination and Water Treatment* **16**, pp. 354 – 380, 2010.

Sharqawy, Mostafa H., John H. Lienhard V, and Syed M. Zubair.(2011) "On Exergy Calculations of Seawater with Applications in Desalination Systems." International Journal of Thermal Sciences 50, no. 2 (February 2011): 187–196.

Sommariva, C. and Syambabu, V. (2001). Increase in water production in UAE. *Desalination*, Elsevier. Vol. 138 (2001)173-179.

Sommariva, C.; Hogg, H. and Callister, K. (2001). Forty-year design life: the next target material selection and operation conditions in thermal desalination plants. *Desalination*, Elsevier. Vol. 136 (2001) 169-176.

Statistical Yearbook. (2019), *Electricity Statistics Yearbook*. Ministry of Electricity and Water, Kuwait 2019.

Temstet, C.; Canon, G., Laborie, J. and Durante, A. (1996). A large high-performance MED plant in Sicily. *Desalination*, Elsevier. Vol. 105 (1996) 109-114.

The Cooperation Council for the Arab States of the Gulf (GCC) General Secretariat. (2014). *Desalination in the GCC- The History, the Present and the Future*. 2014 Second edition. Experts Group, Originating from the Water Resources Committee.

Thu K., Kim Y., Shahzad M. W., Saththasivam J. (2015). Performance investigation of an advanced multi-effect adsorption desalination (MEAD) cycle. *Applied energy* 159 (2015). 469-477.

Utomo, T.; Ji, M.; Kim, P.; Jeong, H. and Chung, H. (2008). CFD analysis of influence of converging duct angle on the steam ejector performance. Proceeding of the International Conference on Engineering Optimization, Rio de Janeiro, June 2008, Brazil.

Villacorte L.O., Tabatabai S. A. A., Dhakal N., Amy G., Schippers J. C., Kennedy M.D. (2014). Algal blooms: an emerging threat to seawater reverse osmosis desalination. *Desalination and water treatment*. Taylor and Francis. 2014.1-11. [This paper summarizes the current state of SWRO technology, the emerging threat of algal blooms to its application and the preventive strategies].

Wade, N. (2001). Distillation plant development and cost update. *Desalination*, Elsevier. Vol. 136 (2001) 3-12.

Wang L. K., B. Sunden, Q. S. Yang (1999) Pressure Drop Analysis of Steam Condensation in a Plate Heat Exchanger, *Heat Transfer Engineering*, Taylor and Francis. 20:1, 71-77.

Wang L., Sunen B., Manglik R. M. (2007). *Plate heat exchangers: Design, applications and performance*. WIT press. UK. 1st edition.[The book presents comprehensive description of plate heat exchangers (PHEs), their advantages and limitations].

Wang, Y. and Lior, N. (2006). Performance analysis of combined humidified gas turbine power generation and multi-effect thermal vapor compression desalination systems — Part 1: The desalination unit and its combination with a steam-injected gas turbine power system. *Desalination*, Elsevier. Vol. 196 (2006) 84-104.

Wangnick, K. (2004). Present status of thermal seawater desalination techniques. http://www.idswater.com/Common/Paper/Paper_51/Klaus.pdf.

Wu J. W., Hu E. J., Biggs M. J. (2012). Thermodynamic cycles of adsorption desalination system. *Applied Energy.* Elsevier. Vol. 90 (2012). 316-322.

Yuanyuan L., Hu E. J., Wu J. W., Biggs M. J. (2014). Recent progress of research and development of adsorption desalination. *Journal of chemical engineering of Japan*. The Society of Chemical Engineers, Japan. 2014. Vol. 47, No. 4, 303-308. [This paper highlights the recent progress on the RandD of the AD technology. A series of experiments has been designed and undertaken to validate the mathematical models].

Zahid Ayub (2003) Plate Heat Exchanger Literature Survey and New Heat Transfer and Pressure Drop Correlations for Refrigerant Evaporators, *Heat Transfer Engineering*, Taylor and Francis. 24:5, 3-16El-

Biographical Sketch

Anwar Omar Binamer received his BSc. in Mechanical Engineering from Faculty of Engineering, University of Aden in 1996, and his MSc. in Mechanical Engineering from Kuwait University in 2003. He then worked in Research Directorate at Kuwait foundation for the Advancement of Sciences (KFAS). Currently he is a Senior Program Officer in Flagship Projects Program. He published several papers in different refereed journals in the fields of energy and desalination. He authored and co-authored one book, two book chapters and several technical reports. His research interests include modeling of thermal desalination systems and processes, energy and exergy analysis of power plants, oil and gas combustion and renewable energy.