

# MED DESALINATION- MODELLING, DESIGN AND OPTIMIZATION

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## 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<sup>3</sup>/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<sup>3</sup>/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<sup>3</sup>/d, a total capacity of 4550 m<sup>3</sup>/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).

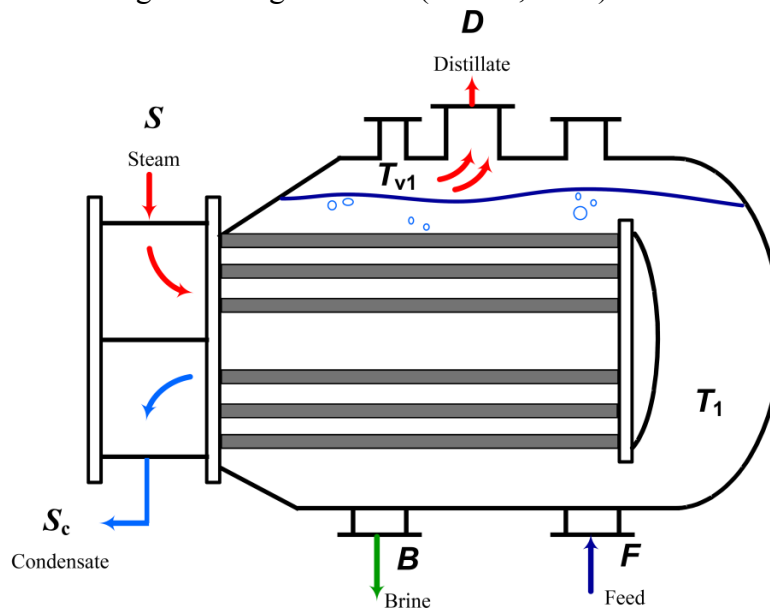


Figure 1. Submerged tube evaporator

(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.

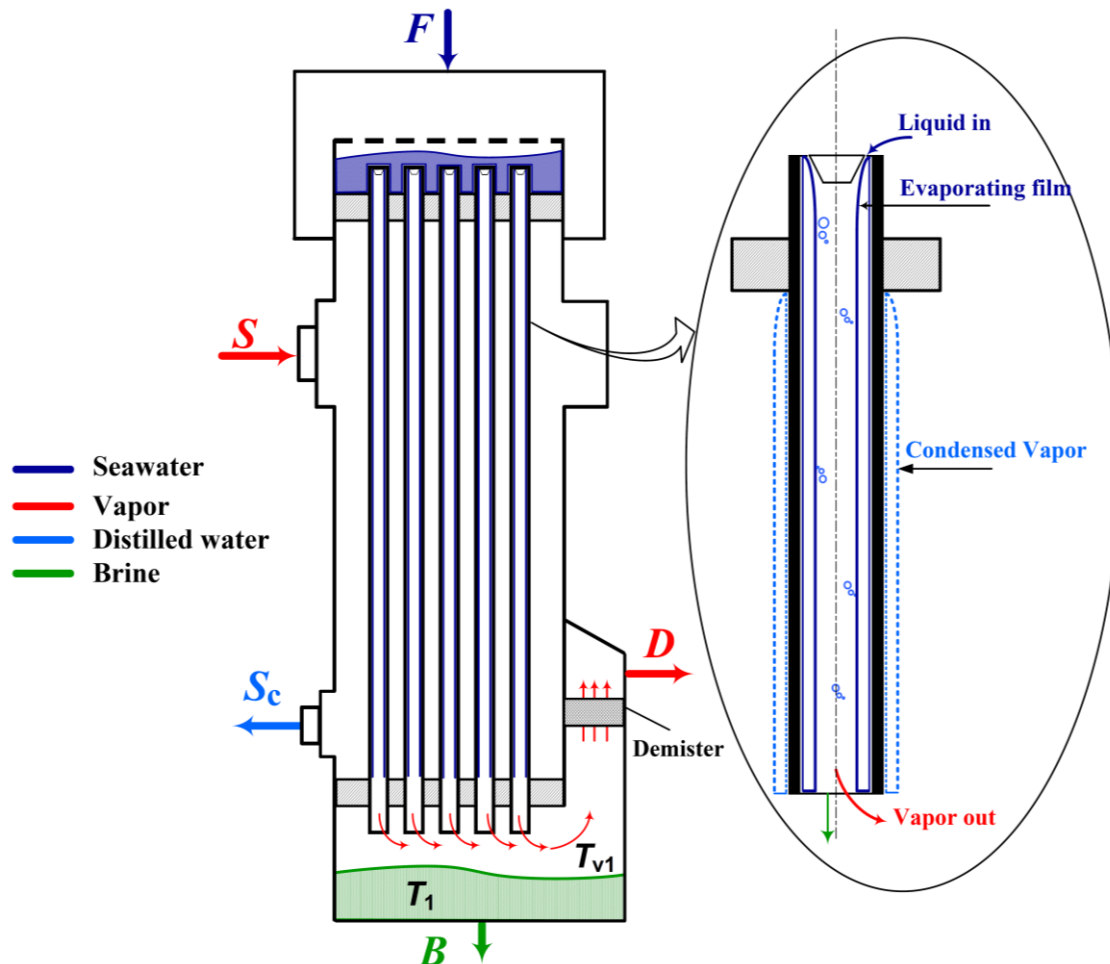


Figure 2. Vertical tube falling film evaporator

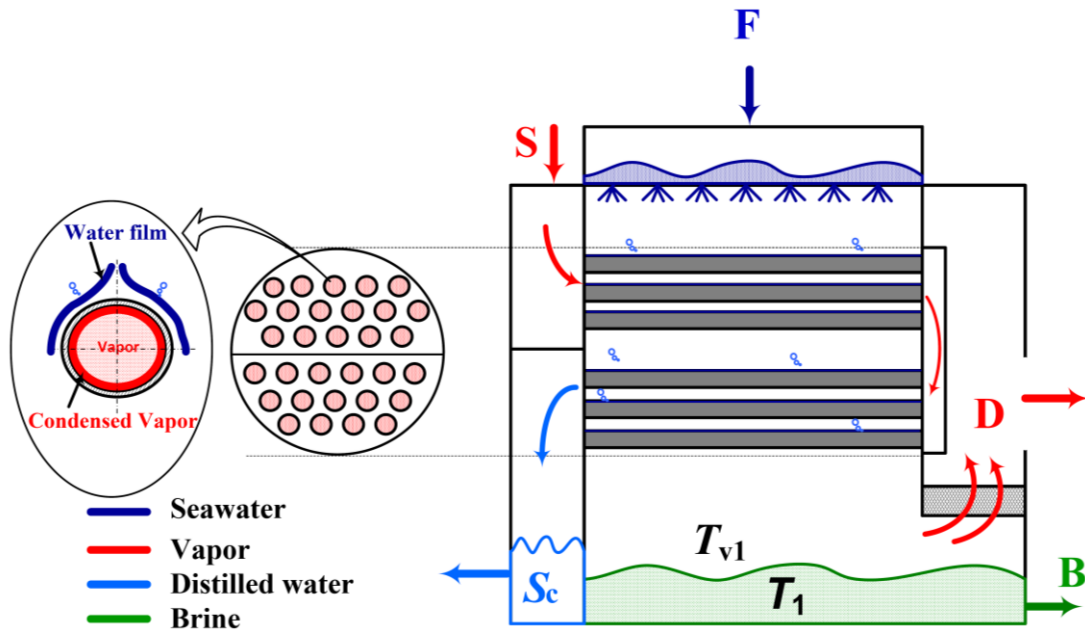


Figure 3. Horizontal tube falling film evaporator

(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](http://www.Alfalaval.com)).

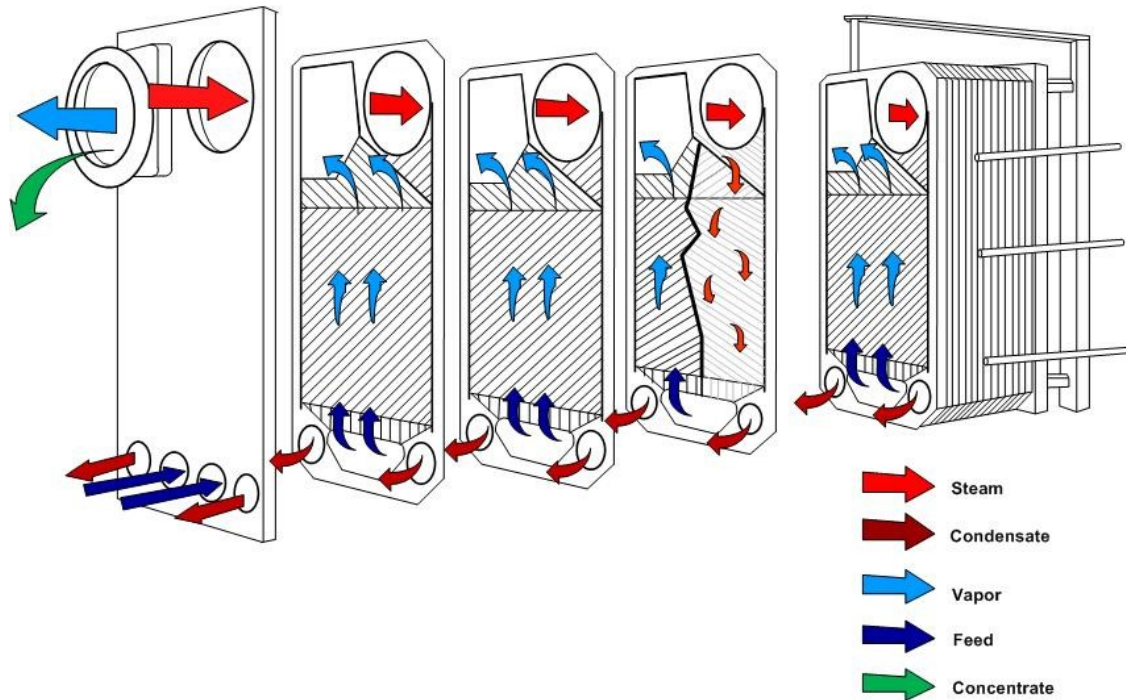


Figure 4. Plate evaporator (Alfa Laval)

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.

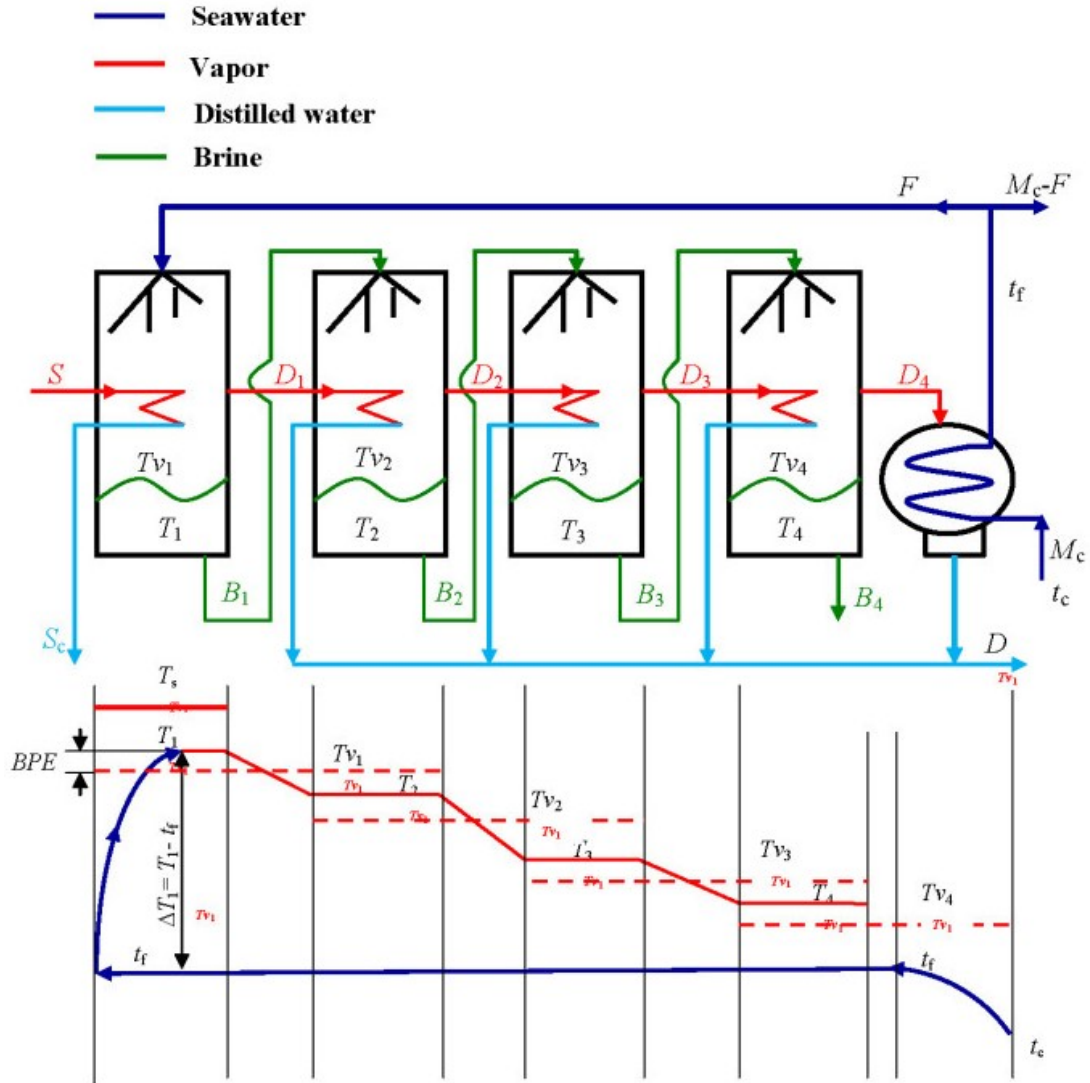


Figure 5. Forward feed arrangement with four effects and its temperature distribution.

(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.

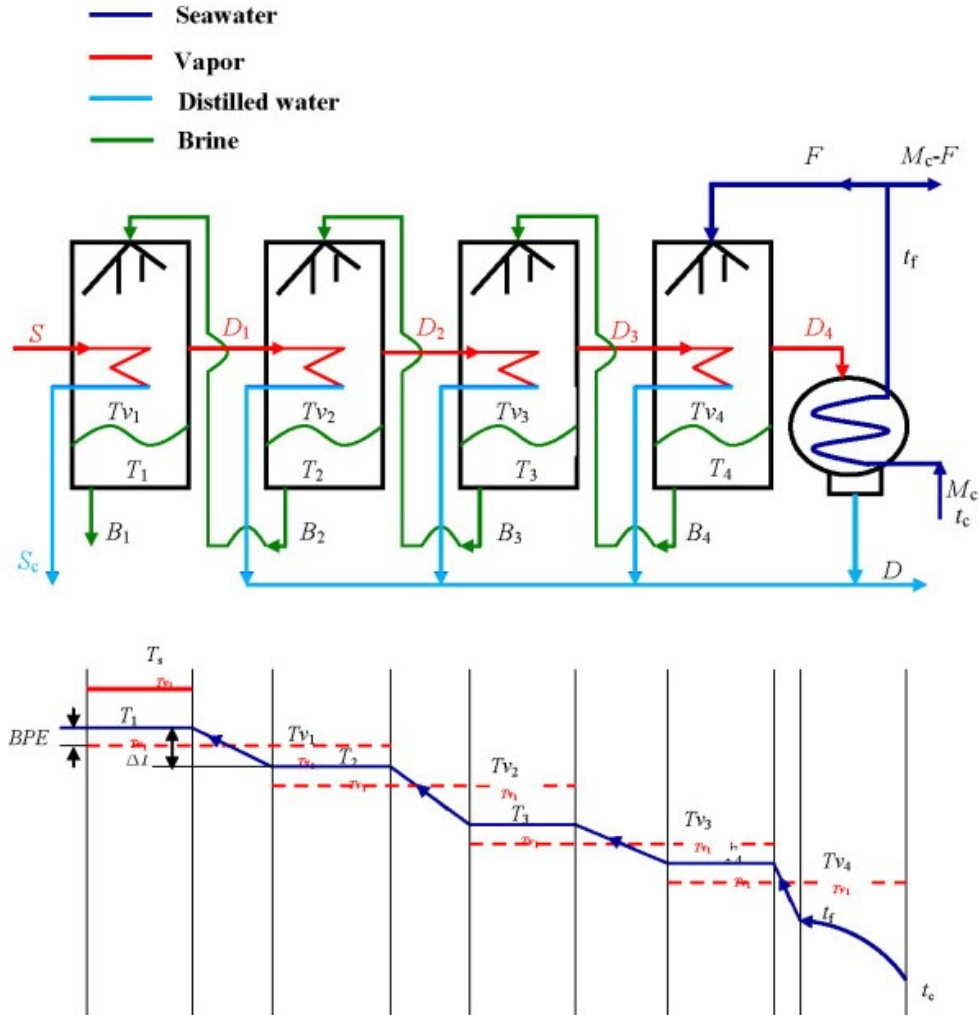


Figure 6. Backward feed arrangement with four effects and its temperature distribution.

#### (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 ( $F/4$ ).

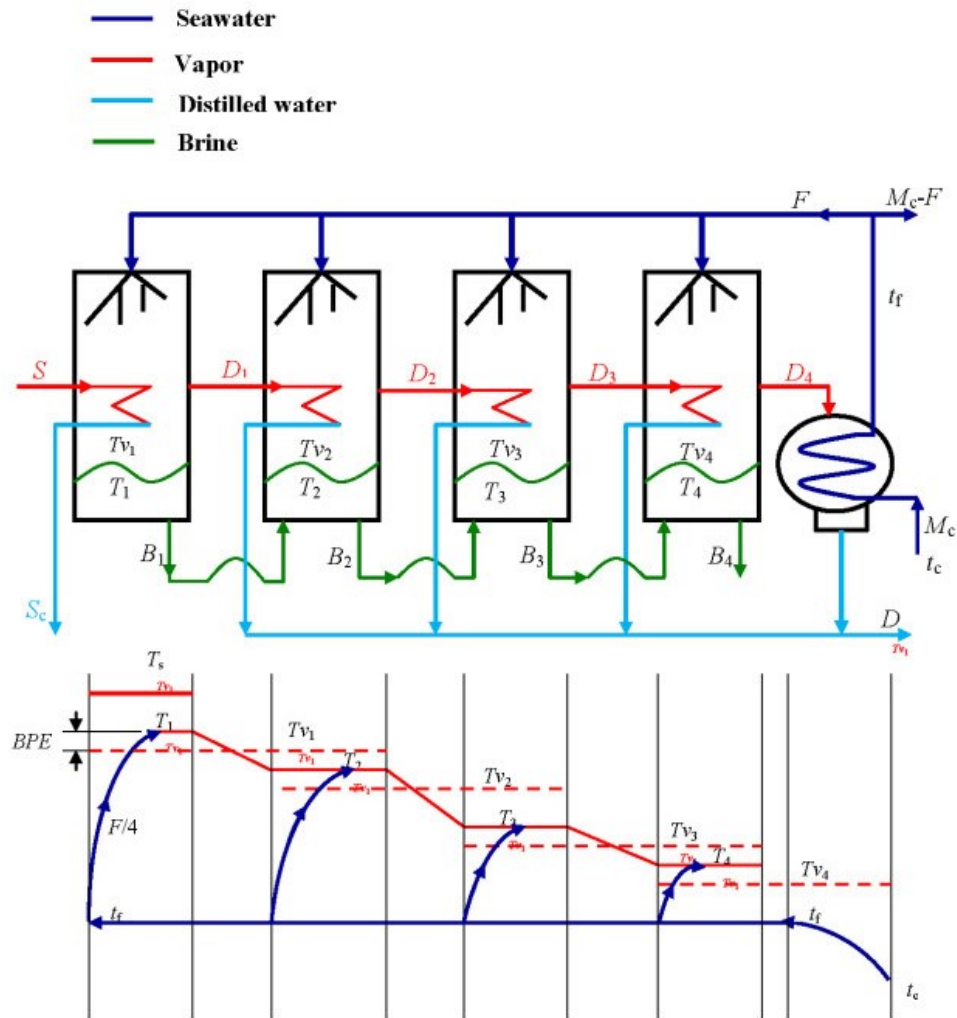


Figure 7. Parallel feed arrangement with four effects and its temperature distribution.

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.

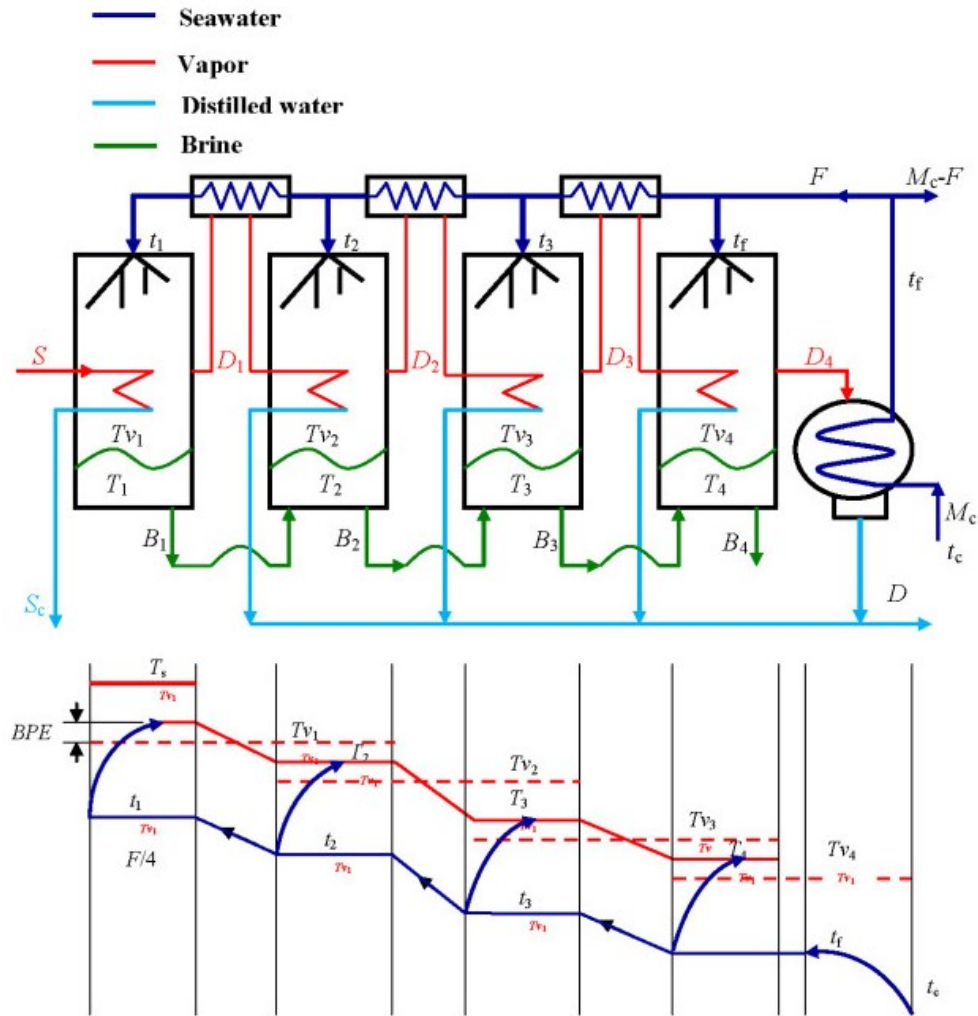


Figure 8. Parallel feed arrangement with regenerative feed heaters

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