

A comprehensive micro-thermal analysis of thermal desalination plants for improving their efficiency

Adel K. El-Feky

Atomic Energy Authority, Nuclear Research Center, Reactor Department, Cairo, Egypt

Email address:

Elfiki02@hotmail.com

To cite this article:

Adel K. El-Feky. A Comprehensive Micro-Thermal Analysis of Thermal Desalination Plants for Improving their Efficiency. *International Journal of Environmental Protection and Policy*. Special Issue: Ferroelectric Nanodomains. Vol. 2, No. 6-1, 2014, pp. 16-25.

doi: 10.11648/j.ijepp.s.2014020601.13

Abstract: The second law efficiency is a main tool for evaluating the irreversibility through a system. Models have been applied for multistage flash (MSF) and mechanical vapor compression (MVC) distillation for evaluating the entropy generation at each component in the process. The minimum work of separation (which is the work consider to extract a unit of pure water from a saline feed water) is considered through the study, the entropy generated due to irreversibility plus that of the in-equilibrium of the discharge brine and its mixing with the seawater are important during the calculation of the minimum separation work, its value for MSF is 0.729 kWh/m³. Exergy is a useful concept in the analysis of systems involving both thermal and mechanical energies. The thermal performance of distillers is assessed based on the first and second laws of thermodynamics. This study focused on the analysis of the energy and exergy of MSF and MVC units. The exergy losses due to irreversibility for the subsystems of the units are evaluated, the specific exergy losses of the MSF unit is at the range of 63 kJ/kg. The exergy destruction in heat recovery and heat rejection sections, brine heater and all the other systems are calculated, these values are 61, 17, 10, and 12% respectively. The study showed that, the second law efficiencies of the MSF unit is around 4 % and for the MVC is around 7%, so these law efficiencies clarify that there are many ways to improve the plant performance by reducing the highest exergy destruction through these systems.

Keywords: Multistage Flash Distillation, Exergy, Second Law Efficiency, Separation Work, MVC

1. Introduction

The need for drinking water has grown fastly over the last century. Nowadays, around 1.7 billion people have shortage for accessing to water, particularly in the developing countries, especially in Middle East, South Asia and Africa. The shortage in the drinking water contributes in 70-80% of diseases in around 90 developing countries.

In order to overcome this shortage, it is important to improve both the water usage and the ways of producing the potable water from non potable one. In the western countries, the water leaves the houses is known as grey water. This type of water is mild contamination and can be reused, this reused water serves in lowering the overall water demand, in this situation the water supply sources will be extended the lifetime of these sources[1].

The continual research and development of desalination processes have resulted in a variety of commercial desalination methods. These processes are classified into

major desalination processes that include multi stage flash, multi effect, vapor compression and reverse osmosis desalination; while the minor processes include solar humidification, freezing and electrodialysis desalination. Nowadays, the multi stage flash and reverse osmosis desalination are the commercial systems that choice for desalination from brackish water and sea water.

From the practical analysis of the operating data of many desalination plants, it is concluded that the second law efficiency of the studied plants is less than 10 %. From these studies, nowadays as it is known that the modern power plants have a second law efficiency of around 50 %, it is clear that there is a wide area for improving these desalination plants. This improvement can be done for the new and existing plants. The new experiences from other systems can be used to enhance the second law efficiency of the desalination plants to approximately the double. The enhancement of the second law efficiency will result in reducing the energy used in the desalination by half.

The thermodynamics analysis of ideal desalination

processes with actual plant operational data is of great importance to the desalination processes. The best tool to do this analysis is the second law. Through this study, there is two main parts for it, the first one is the separation process which is the main point in desalination and the second way is the analysis of the distillation process which are the vapor compression, multi effect and multi stage desalination system[2].

2. Literature Review

O. Hamed et al. [14] have been collected the available data for design and operation of most of SWCC distillers, and utilized it to simulate and analyze the thermal performance of these units. Through their study the impact of different design and operating parameters such as top brine temperature and number of stages on the thermal performance of MSF system is evaluated.

Kamal Mohammadi et al. [11] their study focus on the thermal performance of a small desalination unit, for evaluating the losses through the multistage flash unit, and the study focuses on the environmental impacts associated with the concentrated brine discharge to the Mediterranean sea.

Narmine et al. [7] investigated through their theoretical and experimental work with a MVC system of capacity of 5 m³/d that the potable water production rate increases by increasing the operating temperature, and the evaporator temperature has a good effect on its heat transfer coefficient.

Vesa [17] reviewed a MVC system design parameters, with a design capacity of 500 m³/d. The study analysis showed that the exergy efficiency of the heat exchanger is

around 90 % which is too high compared to other systems. His study concluded that the pre-heaters were very effective although the temperature differences through them are low. This led to reduce the exergy destruction through that unit.

Alasfour et al. [4] their study was performed by using a steady state model for hybrid MSF-MVC system, through their analysis they concentrated on both the 1st and 2nd laws of thermodynamics. Their study concluded that, increasing the temperature drop across the stage leads to increases the specific power consumption which decreases the rate of the productivity. But through the MVC system, increasing the brine temperature decreases the specific heat transfer area. Results indicate also, that increasing the temperature drop across stages leads to increase in exergy destruction.

Mabrouk et al. [18] investigated a hybrid MSF-MVC system; their study showed that the performance ratio (PR) is increased by 2.4 times than conventional MSF system. Also this study indicates that the minimum exergy destruction was reached at a suction pressure of 8 kPa.

3. Distillation Processes

The desalination methods are numerous, In this section, the distillation process will be discussed.

Distillation is a separation process in which a volatile component of a solution is evaporated and then condensed where is the salts remain. The pure water is evaporated by the transfer of heat to a body of saline water, then the pure water vapor is removed from contact with the saline water, then it is condensed by the removal of heat, where the pure water is formed.

3.1. Multi-Stage Brine Recirculation

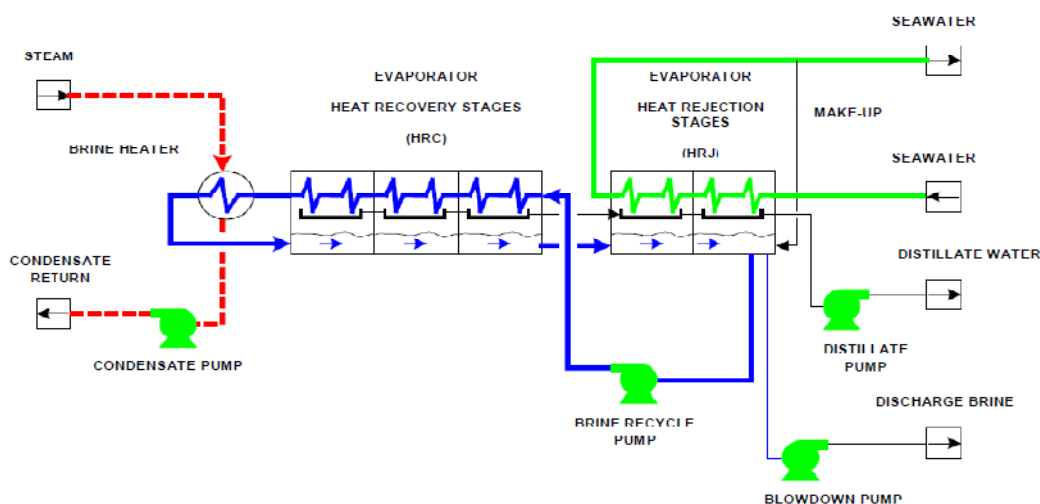


Figure (1). Multi-stage Flash Desalination with Brine Circulation (MSF-BR)

(MSF-BR), a schematic of the MSF-BR system is shown in figure (1). As showed in the diagram, the intake seawater stream is introduced into the condenser tubes of the heat rejection section [2,5]. The temperature of the intake seawater leaving the heat rejection should be close to the

brine temperature of the last stage. The intake seawater divided into two streams, the first one is the cooling seawater stream which is generally discharged into the sea again; the second stream fed again to the bottom of last stage of the heat rejection section. The recirculated brine is taken from the

pool of the last stage of the unit and injected to the condenser of the recovery section. This stream is heated by the latent heat of the vapor produced (flashing) to increase the feed stream, then this brine enter to the brine heater to increase the brine temperature to the maximum value (TBT).

Hot brine enters the flashing stages of the heat recovery section then to the heat rejection section, where a small amount of fresh water vapor is formed by brine flashing in each stage.

Most of the MSF system operates at temperatures below 100°C and under reduced pressures, also the temperatures of the brine to the sea and in the last stage is in the range of 30-40°C.

3.2. Mechanical Vapor Compression

(MVC) is one of the promising low temperature desalination systems. Such systems are characterized by number of advantages, such as: low corrosion rate, minimum scale rates, reliable and flexible operable systems and highly pure distillate [3].

In the mechanical vapor compression (MVC) desalination process, the mechanical compressor is used to recycle the latent heat from the evaporating side to the condensing side

of the evaporating tube. The compressor is used in increasing the process pressure to a high value, where this compression causes the condensing of the vapor that supply the spraying droplets additional heat that increase the amount of generating vapor. The incoming saline water is preheated nearly to its boiling temperature corresponding to the evaporator vapor pressure; this is done by using a heat exchanger where it cools both the brine and distillate. Most of the energy consumed in this process is through the compressor work, as the compressor not only increases the pressure but it reduces the vapor pressure in the evaporator. This desalination method is used in remote areas, resorts and on ships; it contributes of around 2% of the world desalination capacity.

The capacity of SEE-MVC systems has increased over the years from the small production volume to present value of 5000 m³/d. the required source of power is the electricity only. The SEE-MVC consists of four main components: vapor compressor, preheater of intake saline water, evaporator condenser and pumps for brine and distillate [5,7,2]. Figure(2) below presents the flow process of the system

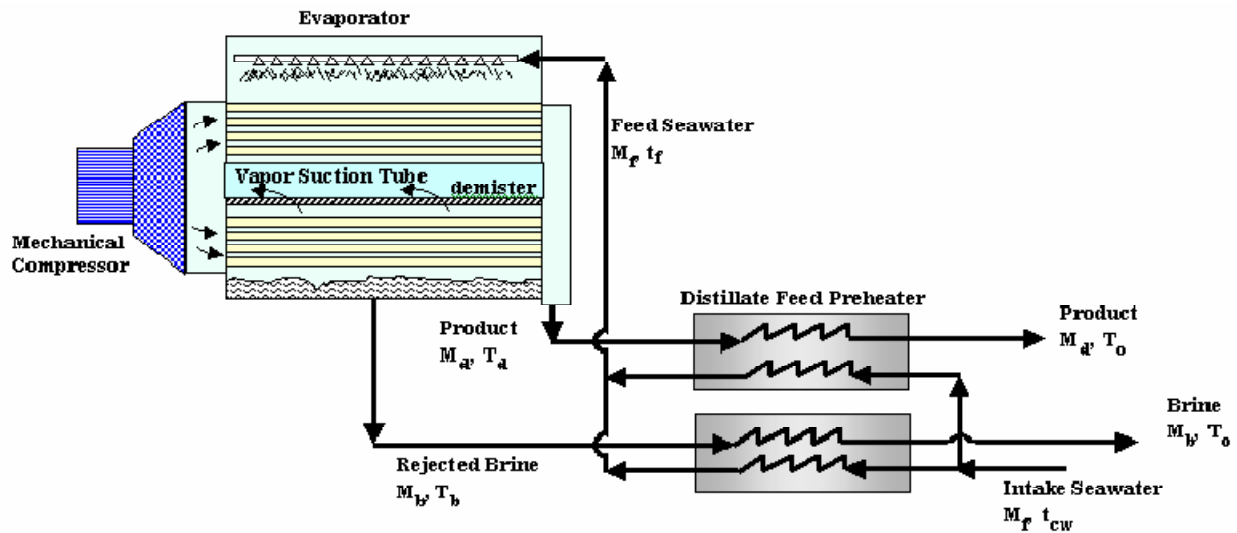


Figure (2). Single Effect Evaporator with Mechanical Vapor Compression (SEE-MVC)

A simple model is considered Aly et al. [7], and the design values and model output are listed in tables3, 4.

4. Thermodynamic Analysis

Through this section, three parameters will be discussed; the first items is to describe the main parameters affecting on the desalination performance, the second item will discuss the separation processes of a mixtures, and the third one is to discuss the second law efficiency for desalination system[5]

a. The main performance parameters

There are many parameters used to describe the performance of the desalination process, the first parameter, the performance ratio (PR) is known as the ratio of the water

product mass flow to the heating steam,

$$PR = \frac{M_d}{M_s} \quad (1)$$

The second parameter, is the gain output ratio (GOR); it is known as the ratio of the enthalpy required for evaporating the distillate to the heat input to the system,

$$GOR = \frac{M_d}{Q/h_{fg}(T_o)} \quad (2)$$

So, for the thermal desalination process; it is clear that both the performance ratio and gain output ratio are very similar. So the relation between the both parameters is the ratio between the latent heat of vaporization at the distillate temperature to it at steam temperature,

$$\text{GOR} = \text{PR} \times \frac{h_{fg}(T_0)}{h_{fg}(T_s)} \quad (3)$$

$$R_r = \frac{M_d}{M_{sw}} \quad (5)$$

The third parameter, is the specific electric consumption (SEC); it is defined as the ratio input work (separation) to the water product flow rate,

$$\text{SEC} = \frac{W_{sep.}}{M_d} \quad (4)$$

There is a difference between both the gain output ratio and the specific electrical ratio in its measuring units, so it cannot be comparable without a conversion factor.

The forth parameter, is the recovery ratio (R_r); it is known as the ratio between the water product flow rate to the feed sea water flow rate

b. Separation Process of a Mixture

A desalination plant essentially separates incoming saline water into product water and brine. The product water contains a low concentration of dissolved salts and brine contains the remaining high concentration of dissolved salts. The plant requires a certain amount of energy in the form of heat or work [2, 16].

The specific Gibbs function g is defined as the combination property as, $g = h - Ts$, if it is assumed to represent the desalination system as a black box to represent the system all over;

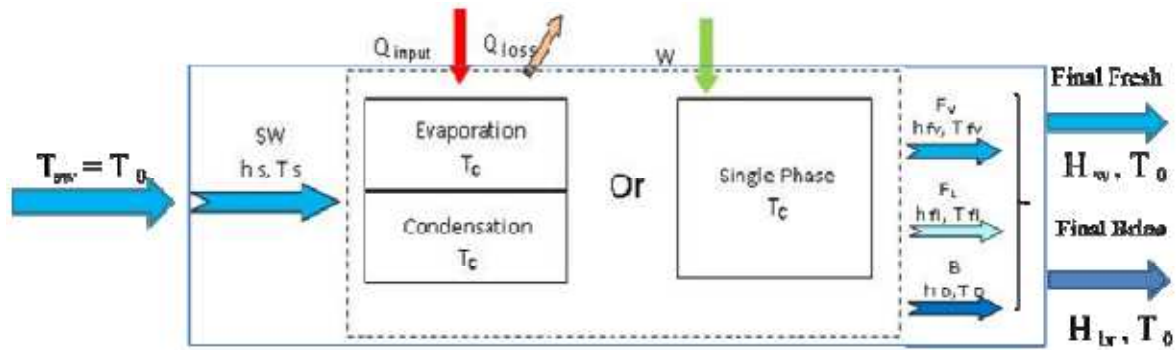


Figure (3). Indicates the control volume which confines all inlets and outlets

Both the separation work and heat required are calculated by the thermodynamics laws over the control volume selected,

From the control volume;

$$\hat{W}_{sep.} + Q + (m \times h)_{sw} = m_d \times h_d + m_b \times h_b \quad (6)$$

Where, m is the mass flow rate, h is the specific enthalpy, s_w is the seawater stream, m_d is the distillate product stream, and b is the brine stream

By dividing the above equation by the ambient temperature T_0 ,

$$\hat{S}_{gen.} + \frac{Q}{T_0} + (m \times S)_{sw} = m_d \times S_d + m_b \times S_b \quad (7)$$

Where, S is the specific entropy

From the specific Gibbs function g , and the above two equations

$$\hat{W}_{sep.} - \hat{S}_{gen.} \times T_0 + (m \times h)_{sw} - (m \times S)_{sw} = (m \times h)_d - (m \times S)_d \times T_0 + (m \times h)_b - (m \times S)_b \times T_0 \quad (8)$$

$$\hat{W}_{sep.} = (m \times g)_d + (m \times g)_b - (m \times g)_{sw} + \hat{S}_{gen.} \times T_0 \quad (9)$$

If the operation process is in the limit of reversible operation, i.e. the entropy term is zero

($\hat{S}_{gen.} \times T_0 = 0$, at the limit of reversible)

$$\therefore \hat{W}_{sep.} (\text{least}) = m_d \times g_d + m_b \times g_b - m_{sw} \times g_{sw} \quad (10)$$

If the heat is used to produce desalinated water for a desalination system instead of the work, so the heat of

separation is the predominate parameter.

For Carnot engine,

$$Q_{sep.} = \hat{W}_{sep.} + Q \quad (11)$$

$$\frac{Q_{sep.}}{m_d} = \frac{\hat{W}_{sep.}}{m_d} + \frac{Q}{m_d} \quad (12)$$

$$\therefore \frac{\hat{W}_{sep.}}{m_d} = \frac{Q_{sep.}}{m_d} \left[1 - \frac{T_0}{T_H} \right] \quad (13)$$

For the reversible operation heat engine;

$$\begin{aligned} \therefore \frac{Q_{sep.}}{m_d} &= \frac{\hat{W}_{sep.}}{m_d} \left[\frac{1}{1 - \frac{T_0}{T_H}} \right] \\ &= \frac{\hat{W}_{sep.} + \hat{S}_{gen.} \times T_0}{m_d \left[1 - \frac{T_0}{T_H} \right]} \end{aligned} \quad (14)$$

From the mass balance, salinity balance and above equations,

$$m_{sw} = m_d + m_b \quad (15)$$

$$m_{sw} \times X_{sw} = m_d \times X_p + m_b \times X_b$$

$$X_b = \frac{m_{sw} \times X_{sw} - m_d \times X_d}{m_b} = \frac{X_{sw}}{1 - R_r} - \frac{R_r \times X_d}{1 - R_r} \quad (16)$$

$$\text{as, } \frac{\hat{W}_{sep.}}{m_d} = g_d + \frac{m_d}{m_d} \times g_b - \frac{m_{sw}}{m_d} \times g_{sw}$$

$$\therefore \frac{\hat{W}_{sep.}}{m_d} = g_d + \frac{m_{sw} - m_d}{m_d} \times g_b - \frac{m_{sw}}{m_d} \times g_{sw} \quad (17)$$

It is important to observe from the above equation, that the minimum work of separation is affected by the salinity of both the feed seawater and the product streams and not affected by the way used for desalination.

$$\frac{\dot{W}_{sep}}{m_d} = g_d + \left[\frac{1}{R_r} - 1\right] \times g_b - \frac{1}{R_r} \times g_{SW} \quad (18)$$

The minimum separation work can be calculated from equation (18), for different water salinity and recovery ratios at a certain temperature. It is obvious from this equation that, at a certain degree of salinity increasing the recovery ratio from 0 percent to 100 percent the separation work is increased and it decrease with decreasing the salinity at the same recovery. Figure (4) below illustrates the minimum separation work at different salinities of the incoming feed water with pure product and different recovery ratio. These curves indicate also, the lowest and highest minimum separation works which corresponding to 0 and 100 percent recovery.

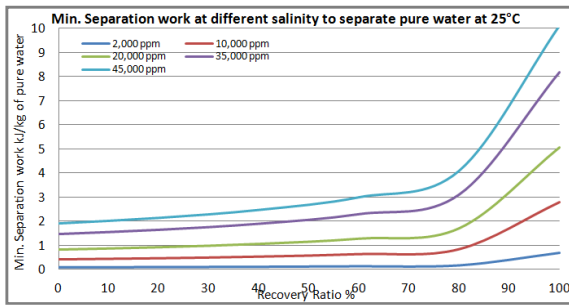


Figure (4). Indicates the minimum separation at different salinities with pure water product

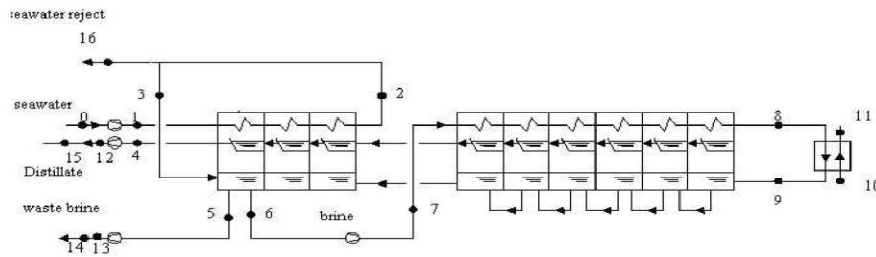


Figure (5). Illustrates the Multi-Stage Flash unit flow sheet process (MSF-BR)

5.2. Msf Plant Exergy Analysis

The Multi-Stage Flash (MSF) unit under this study is analyzed:

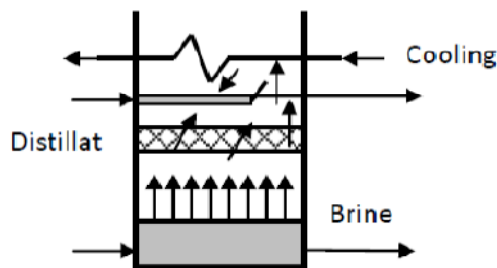


Figure (6). Illustrates the details of one stage of the MSF process

It is concluded that, the minimum separation work increases strongly at higher recovery ratios greater than 80 percent so it is required to avoid the design stages of any desalination units to work under a recovery ratio of 80 percent. It is clear that the work required is dependant completely on the feed and product salinity (increase the feed salinity increase the required work and increase the product salinity reduced the required work).

5. Exergy Analysis of Desalination Plant

5.1. Msf Plant Description

The MSF unit consists of 22 stages, the flow diagram of this unit is shown in figure (5), it works at a salinity of 46,500 ppm and feed seawater temperature at 35°C and rate of 2397 kg/s, where a value of it is returned back to the pool of the last stage at a temperature of 43.3°C and at a rate of 808 kg/s, after mixing with the brine in its salinity goes to 64,828 ppm [2,11,14].

The circulated pump delivered a rate of flow of 3621 kg/s to the recovery section, so its temperature increases to 85°C, then it enters to the brine heater to raise its temperature to 90.8°C.

The brine heater uses steam at a rate of 37.02 kg/s at a temperature of 98.9°C.

The condensates vapor through all stages at a rate of 272 kg/s. The salinity of the brine discharge to the sea at a rate of 536 kg/s and salinity of 70,093 ppm.

5.3. MSF Unit Overall Exergy Analysis [13, 15]

Total specific exergy stream consists of,

$$E_{total} = E_{th} + E_{ch} + E_{po} + E_{k.e}$$

Both the E_{ch} , E_{po} , $E_{k.e}$ can be ignored, so the total exergy can be expressed as,

$$E_{total} = E_{th} = (h - h_0) - T_0(s - s_0) \quad (19)$$

$$\text{Exergetic efficiency } (\eta_{II}) = \frac{W_{min.}}{E_{in.}} \quad (20)$$

$$\text{Exergetic Destruction} = E_{in.} - E_{out.} \quad (21)$$

For stage efficiency

$$\eta_{II}(\text{stage}) = \frac{E_{usefull}}{E_{in.stage}} = \frac{(E_{in.} - E_{out.})_{distillate} + (E_{out.} - E_{in.})_{cooling}}{(E_{in.} - E_{out.})_{brine}} \quad (22)$$

For standard condition, at $T_0 = 308$ K, $P_0 = 101.3$ KPa, and salinity = 64,500 ppm (which is referred to the dead state). At these conditions, the specific heat of salt can be taken to be $C_{p_s} = 0.8368$ kJ/kg.K, also the enthalpy and entropy of the salt at the ambient conditions are $h_{s_0} = 29.288$ kJ/kg and $s_{s_0} = 0.1009175$ kJ/kg.K.

The enthalpy and entropy of salt at certain temperature T can be computed from the following equations [11].

$$h_s = h_{s_0} + C_{p_s} * (T - T_0) \quad (23)$$

$$s_s = s_{s_0} + C_{p_s} \ln(T/T_0) \quad (24)$$

The molar mass of NaCl = 58.5 kg/kmol and the molar mass of water 18 kg/kmol. For seawater of salinity of 64,500 ppm; the mass fraction of salt (mf_s) = 0.0645 and the mass fraction of water = 0.9355.

The sum of the Mole fraction (X) of salt and water at the feed seawater equal 1.

$$\text{i.e.) } X_s + X_w = 1$$

$$X_s = \frac{M_w}{M_s \left(\frac{1}{mf_s} - 1 \right) + M_w} \quad (25)$$

$$\therefore X_s = \frac{18}{58.5 \left(\frac{1}{0.0645} - 1 \right) + 18} = 0.02077 \approx 2.077 \%$$

$$\therefore X_w = 1 - 0.02077 = 0.9792 \approx 97.92 \%$$

So, the molar salinity of the feed seawater is around 2.077 %. The enthalpy and entropy of salt and water mixture (as assumed that the seawater is an ideal solution) can be calculated from these equations:

$$h = mf_s * h_s + mf_w * h_w \quad (26)$$

$$s = mf_s * s_s + mf_w * s_w \quad (27)$$

The exergy rate for a flow for any fluid stream can be calculated using (Cengel and Boles, 1998)

$$\text{Exergy rate (E)} = m [h - h_0 - T_0(s - s_0)] \quad (28)$$

By using the above equations, the exergy at each point of the system can be evaluated. This is illustrates in tables (1, 2).

Table (1). Indicates the specific enthalpy and entropy of both Salt and Water

State	T (K)	P (Bar)	hs (kJ/kg)	Ss (kJ/kg.K)	hw (kJ/kg)	Sw (kJ/kg.K)
0	308	1.013	29.288	0.1009175	146.727	0.50516
1	308	1.68	29.288	0.1009175	146.727	0.50516
2	316.3	1.15	36.233	0.1231691	181.407	0.61623
3	316.3	1.15	36.233	0.1231691	181.407	0.61623
4	314.4	0.0796	34.644	0.1181274	173.469	0.59107
5	316.3	0.0796	36.233	0.1231691	181.407	0.61623
6	316.3	0.0796	36.233	0.1231691	181.407	0.61623
7	316.3	6.35	36.233	0.1231691	181.407	0.61623
8	358	6.35	71.128	0.2268	355.854	1.13441
9	363.8	6.35	75.981	0.240248	380.207	1.20194
10	371.9	0.974	Brine H.	Brine H.	414.279	1.29463
11	371.9	0.974	Brine H.	Brine H.	414.279	1.29463
12	314.5	5.78	34.727	0.1183935	173.887	0.59239
13	316.3	2.92	36.233	0.1231691	181.407	0.61623
14	308	1.013	29.288	0.1009175	146.727	0.50516
15	308	1.013	29.288	0.1009175	146.727	0.50516
16	308	1.013	29.288	0.1009175	146.727	0.50516

Table (2). Indicates the enthalpy and entropy of saline water

state	T (K)	X (g/litre)	m (kg/s)	h (kJ/kg)	S(kJ/kg.K)	Sp. Exergy(kJ/kg)
0	308	46.5	2397	139.152	0.4791	0
1	308	46.5	2397	139.2141	0.4791	0.0621
2	316.3	46.5	2397	172.043	0.5844	0.4787
3	316.3	46.5	808	172.034	0.5844	0.4787
4	314.4	0	272	173.469	0.59107	10.521
5	316.3	70.093	536	171.231	0.58166	-3.475
6	316.3	64.828	3621	171.995	0.58426	-2.668
7	316.3	64.828	3621	171.955	0.58426	-1.985
8	358	64.828	3621	337.395	1.07557	12.035
9	363.8	64.828	3621	360.4838	1.13959	15.526
10	371.9		37.02	414.279	1.29463	389.002
11	371.9		37.02	414.279	1.29463	0
12	314.5	0	272	173.887	0.59239	11.046
13	316.3	70.093	536	171.2313	0.58166	-3.322
14	308	70.093	536	138.4953	0.47683	-3.912
15	308	0	272	146.727	0.50517	10.332
16	308	46.5	1589	139.152	0.4791	0

The intake stream salinity taken as the dead state “0”, so the exergy at that point is zero and the exergies of the brine streams are negative “-ve” as it is clear in the above table due to its salinities are above the salinity of the dead state.

It is obvious that when the salinity is above the salinity above the dead state the fluid stream need an input work to reduce the stream salinity, and vice versa for the pure water, it can produce work.

The minimum exergy is the difference between the exergies of the output streams and the input stream,

- The min. separation work:

$$\begin{aligned}\text{The Exergy (min.) rate} &= E_{14} + E_{15} - E_0 = 713.472 \text{ kW} \\ &= 2.62 \text{ kJ/kg} \\ &= 0.729 \text{ kWh/m}^3\end{aligned}$$

@ T = 35°C (the min. separation work curves above)

- The exergy changes through the pumps:
For the recirculated Pump,

$$\Delta E_{\text{rec.}} = E_7 - E_6 = 2473.143 \text{ kW}$$

For distillate Pump,

$$\Delta E_{\text{dist.}} = E_{12} - E_4 = 142.8 \text{ kW}$$

For brine Pump,

$$\Delta E_{\text{brine}} = E_{13} - E_5 = 82.008 \text{ kW}$$

For intake Pump,

$$\Delta E_{\text{intake}} = E_1 - E_0 = 148.853 \text{ kW}$$

$$\therefore E_{\text{pumps}} = 2846.804 \text{ kW}$$

The pump system efficiency is assumed to be 80 %, the total pumps exergy equal to:

$$\text{Total pumps } E = E_{\text{pumps}} / \eta_p$$

$$\therefore \text{Total pumps } E = 2846.804 / 0.8 = 3558.505 \text{ kW}$$

- The brine heater, the exergy supply to the brine by heating steam,

$$\text{Exergy rate due to steam } (E_{\text{steam}}) = m_s * (h_{fg} - T_0 * s_{fg}) \quad (29)$$

$$E_{\text{steam}} = 14340.0672 \text{ kW}$$

$$\therefore E_{\text{total in.}} = E_{\text{pumps}} + E_{\text{steam}} = 17898.5722 \text{ kW}$$

The Second law Efficiency of the MSF unit under study equal:

$$\eta_{II} = E_{\text{min.}} / E_{\text{total in.}} = 713.472 / 17898.5722 = 3.986 \% \sim 4 \%$$

it is clear, that the second law efficiency is very low for the MSF, as the useful value is only equal to 713.5 kW through very high consumed energy of 17,899 kW, i.e the total destruction energy of the unit is equal to 17,185.5 kW

For calculating the exergy destruction through the components of the MSF unit:

1. Energy destruction for the cooling brine,

$$E_{\text{Des. Cooling brine}} = E_2 - (E_3 + E_{16}) = 783.6494 \text{ kW} \quad (4.56\%)$$

$$2. \quad E_{\text{Des. distillate}} = E_{12} - E_{15} = 194.208 \text{ kW} \quad (1.13\%)$$

$$3. \quad E_{\text{Des. brine}} = E_{13} - E_{14} = 316.24 \text{ kW} \quad (1.84\%)$$

4. Exergy destruction for system pumps:

$$E_{\text{Des. Pumps}} = 3558.505 - 2846.804 = 711.701 \quad (4.14\%)$$

5. The exergy destruction through both the recovery and rejection sections (Edes.(rec.+rej.):

$$E_{\text{Des.(rec.+rej.)}} = E_{\text{in.}} - E_{\text{out.}} = 13480.1407 \text{ kW} \quad (78.44 \%)$$

6. The exergy destruction through the brine heater

$$\therefore E_{\text{Des. BH.}} = 1759.943 \text{ kW} \quad (10.24 \%)$$

It is clear that, the highest destruction in the MSF unit is through the hear recovery and heat rejection section by a value of 78%, so this indicates that the process through the flashing in both recovery and rejection is very low efficient. This followed by the exergy destruction through the brine heater section by a value of 16%, followed by the pumps and cooling brine by a value of 4.27% and 4.98% respectively as indicated in figure (7).

For all distillers, the major exergy destruction has been occurred in the recovery section where it can reach to around 60 percent.

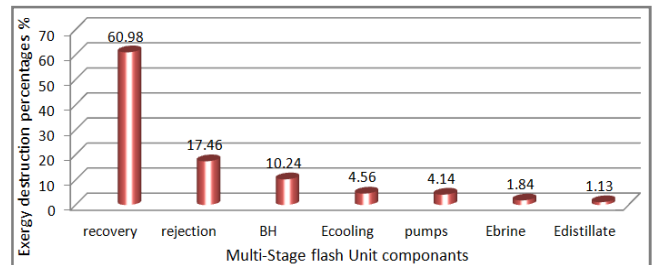


Fig (7). Exergy destruction through MSF unit Components

So the specific exergy losses through the brine heater, the rejection section, and the losses through the outlet streams is lower than the recovery section. This is because of the greater the heat transfer area of the recovery section than the sum of the brine heater and rejection section area (greater by several times).

The unit under study is working at a top brine temperature of 90°C and at a performance ratio of 7.5 at these conditions, the specific exergy losses at the range of 63 kJ/kg. The next figure represents a comparison of the exergy losses between this study and other two plants, the differences between these units are due to many parameters may be salinity, pumps efficiency, plant capacity, top brine temperature and accurate calculation.

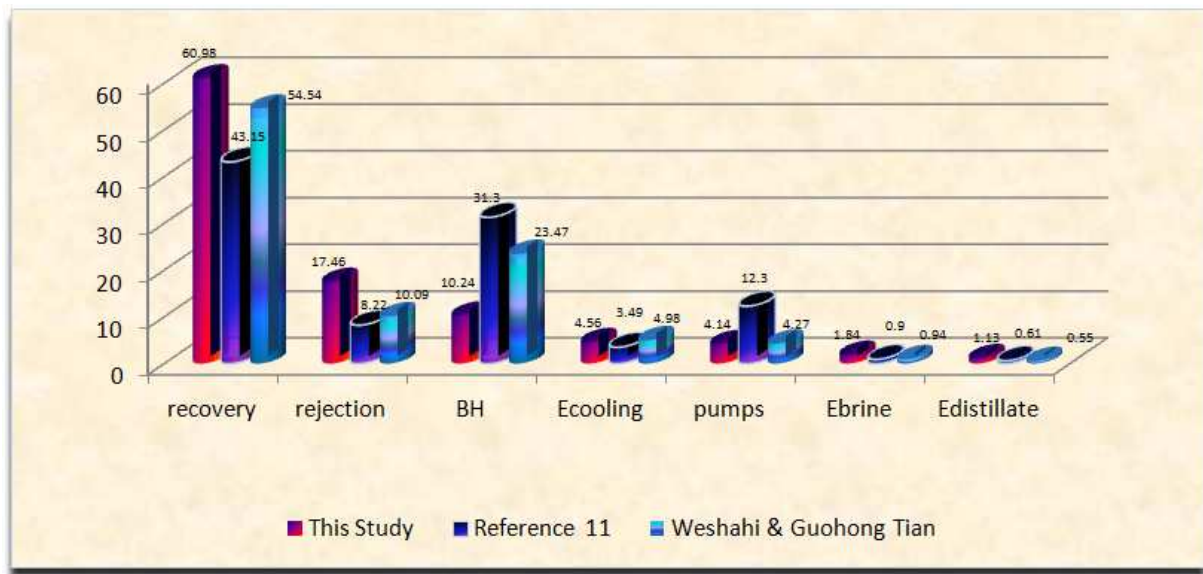


Figure (8). indicates a comparison of the exergy losses between this study and other two plants

5.4. Single Effect Evaporator Mechanical Vapor Compression (SEE-MVC)

A single effect evaporator (SEE-MVC) model is considered. A model developed by Narmine et al. [7] is chosen for this study, the design data and model results are shown in tables 3, 4.

Table (3). Design data for MVC unit

Parameters	value
Seawater inlet temperature	20°C
Seawater inlet salinity	35,000 ppm
Discharge brine salinity	10 ppm
Top brine temperature	69.5°C
ΔT evaporator-condenser	3.8°C
Recovery ratio (R)	47%
Isentropic compressor efficiency	85%
Compressor inlet pressure	30 kPa

Some of the equations used for calculating the exergy generated and the exergy destruction through the unit [4,15,17,18]:

- The exergy balance for the evaporator can be expressed as,

$$(E_f + E_s)_{in} = E_d + E_b + E_{des, evap.} \quad (30)$$

- For the specific exergy,

$$E_{spec} = \sum E_{thermal} + E_{chemical} + E_{pressure}$$

The chemical and pressure exergy can be neglected, so the specific exergy can be taken to be thermal only.

$$\therefore E_{spec} = (h - h_0) - T_0(s - s_0) \quad (31)$$

The destructive exergy through the evaporator can be evaluated by:

$$E_{des, evap.} = E_{in} - E_{out}$$

$$= m_s * (e_{Comp.o} - e_{cond.}) + m_f * e_f - m_b * e_b - m_d * e_v \quad (32)$$

- For the compressor,

$$W_{comp.} = m_d * (h_s - h_v) / \eta \quad (33)$$

$$E_{Des, comp.} = P_{shaft} - m_d (e_{comp.o} - e_v) \quad (34)$$

The exergy losses for the MVC system:

The rate of the work lost in a process is equal to the rate of dissipated exergy. So the rate of the exergy destruction D which is related to the created entropy production " S^{cr} " known by Maxwell-Gouy-Stodola (MGS) equation[3],

$$\frac{dD}{dt} = -T_0 * \frac{dE}{dt} = -T_0 * m * \Delta X \quad (35)$$

where, the entropy creation S^{cr} and exergy destruction are losses and ΔX is the driving force related to the flow rate m .

$$\therefore X = \frac{1}{m} \frac{dS}{dt} = S^{cr} \quad (36)$$

For the unit under study:

As seen in the above table the unit operates at a temperature of 70°C

For a boiling point elevation corresponding to a temperature of 70°C and salinity of 35,000 ppm;

The BPE= 0.75°C

$$T_v = 70 - 0.75 = 69.25^\circ\text{C}$$

$$\Delta T = 3.5^\circ\text{C}, \quad T_c = 69.25 + 2.5 = 71.75^\circ\text{C}$$

$$T = \frac{T_v + T_c}{2} = (69.25 + 71.75) / 2 = 70.5^\circ\text{C}$$

$$h_{fg} = 2331.5 \text{ kJ/kg} = 41967 \text{ J/mol}$$

$$\Delta X = h_{fg} * \Delta T / T^2 = 41967 * 2.5 / (343.5^2) = 0.88 \text{ J/mol. K}$$

$$\text{Destructive exergy} = T_0 \cdot \Delta X = 293 \cdot 0.88 = 260.6 \text{ J/mol.}$$

$$= 260.6 / (18 \cdot 3.6) = (5/24) \times 4 \text{ kW} = 0.83 \text{ Kw}$$

The second law efficiency (η_{II}) = 6.4 %

The model output data can be summarized in the following table,

Table (4). Model output data

Parameters	value
Specific electricity consumption	14 kWh/m ³
Compression ratio (Cr)	1.3
Product water temperature	26.5°C
Discharge brine temperature	25°C
Second law efficiency	6.4 %

6. Conclusion

Increasing of the demand of fresh water is the main driving force for developing of the seawater desalination technologies all over the world and especially in the Middle East area. So this study is concluded in the analysis and the enhancement for the cases studied:

6.1. Analysis

1. The overall exergy efficiency of this MSF unit is only around 4 % which offers potential for improvement.
2. The exergy efficiency is the highest in the first stage and going down in the direction of the last stage.
3. For this MSF unit, the study indicates that around 78 % of exergy destruction happened through the distillers (stages). Most of it occurs through the heat recovery section, this is clear in figure (7), and the specific exergy losses at the range of 63 kJ/kg.
4. Periodically, the Acid cleaning showed be performed, this leads to enhance the plant performance and at the same time this reduced the exergy destruction,
5. The overall exergy efficiency of the MVC unit is around 7 % which offers potential for improvement.

6.2. Enhancement

1. Recovering the waste heat from the hot distillate water can enhance the exergy efficiency of the MSF units.
2. Using low grade steam as a heating source is efficient for thermal desalination plants.
3. The hot distillate extract can be used as a source of powering other processes such as MED.
4. Using high efficient pumps of (89%) can reduce the electrical consumed power as the destructive energy through pumping system reach 4 %.
5. Applied of the co-generation systems, by coupling the power plants with desalination plants, through this the waste heat of the power plants as a heat source for desalination units, this will enhance the performance of the desalination plants.

Nomenclature

Symbols

<i>BH</i>	brine heater
<i>BPE</i>	Boiling point elevation, °C
<i>C_p</i>	Specific heat capacity, kJ/kg. K
<i>CR</i>	Compression ratio
<i>E</i>	rate of exergy kJ/s
<i>G</i>	specific Gibbs function
<i>GOR</i>	gain output ratio
<i>GR</i>	Gain ratio
<i>H</i>	Enthalpy, kJ/kg
<i>h_f</i>	Saturated enthalpy, kJ/kg
<i>h_{fg}</i>	Latent heat, kJ/kg
<i>M</i>	mass flowrate kg/s
<i>M_f</i>	mass fraction
<i>MSF</i>	Multi stage flash system
<i>n</i>	Number of stage
<i>P</i>	Pressure, kPa / bar
<i>Ppm</i>	Part per million
<i>PR</i>	performance ratio
<i>Q</i>	heat kJ
<i>R_r</i>	recovery ratio
<i>S</i>	entropy generation rate kJ/k
<i>SEC</i>	specific electric consumption
<i>SEE-MVC</i>	single effect evaporator
<i>T</i>	temperatur K
<i>TBT, T_i</i>	Top brine temperature, °C
<i>T_f</i>	Feed seawater temperature, °C
<i>T_o</i>	Environment state temperature, K
<i>T_v</i>	Saturated vapor temperature, °C
<i>W</i>	work kW
<i>X</i>	Salt concentration, ppm
<i>ΔT</i>	Temperature difference per stage, oC
Subscripts	
<i>0, amb.</i>	dead state, ambient condition
<i>B</i>	Brine
<i>comp.</i>	compressor
<i>cond. / c</i>	condenser
<i>cr</i>	Creation
<i>D</i>	Distillate
<i>Des.</i>	destructive
<i>evap.</i>	evaporator
<i>F</i>	Feed
<i>gen.</i>	generation
<i>H</i>	heat reservoir k
<i>in.</i>	inlet, incoming
<i>out.</i>	Outlet
<i>s</i>	steam /salt
<i>sep.</i>	separation
<i>Sw</i>	Seawater
<i>V</i>	Vapor
<i>W</i>	Water

References

- [1] S. Kazadi, Y. Hong, C. Chau, A. Chaudhary, A. Chaudhary, J. Park, J. Liu, M. Kim, D. Kim, S. Kim Desalination Powered By Entropy
- [2] Yunus Cerci, Yunus Cengel, Byard Wood, Nafiz Kahraman, and E. Sinan Karakas Desalination and Water Purification Research and Development Program, 2003
- [3] K. S. Spiegler, Y. M. El-Sayed the energetic of desalination processes, Desalination 134 (2001) 109 - 128
- [4] Fuad N. Alasfour, Hassan K. Abdulrahim, the effect of stage temperature drop on MVC thermal performance, Desalination 265 (2011) 213-221
- [5] Water desalination technologies in the ESCAWA member countries, United Nations, New York, 2001
- [6] Huseyin Yapici, Nesrin Kayatas, Nafiz Kahraman and Gamze Basturk, Numerical study on local entropy generation in compressible flow through a suddenly expanding pipe, Entropy 2005, 7, 38-67
- [7] Narmine H. Aly, Adel K. El-Fiqi, Mechanical vapor compression desalination systems-a case study, Desalination 158 (2003) 143-150
- [8] Devin L Shaffer, Laura H Arias Chavez, Moshe Ben-Sasson, Santiago Romero-Vargas Castrillon, Ngai Yin Yip, and Menachem Elimelech, Desalination and reuse of high salinity shale gas produced water: Drivers, Technologies, and Future Directions, Environmental Science & Technology, 2013
- [9] Goran Wall and Mei Gong, on exergetics, Economics, and Desalination, <http://www.exergy.se/>
- [10] K Ghana Sundari, Veerabhadra Ponnaganti and T Michael N Kumar, Exergy analysis of a low temperature thermal desalination system, Int. J. Mech. Engineering and Robotics Research, vol. 2, No. 1, January 2013
- [11] Kamal Mohammadi, Anissa Talamali, Youcef Smaili, Imane Saadoun, Aomar Ait-Aider, Environmental impact of seawater desalination plants: case study in Algeria, American Journal of Environmental Protection, 2013; 2 (6):141-148
- [12] Mostafa H. Sharqawy, John H. Lienhard V and Syed M. Zubair, Thermophysical properties of seawater: A review of existing correlations and data, Desalination and water treatment, 16 (2010) 354-380
- [13] Anwar Binamer, Second law and sensitivity analysis of large ME-TVC desalination units, Desalination and water treatment, (2013) 1-12
- [14] Osman A. Hamed, Mohammad AK Al-Sofi, Monazir Imam, Ghulam M. Mustafa, Khalid Ba-Mardouf and Hamad Al-Washmi, thermal performance of multistage flash distillation plants in Saudi Arabia, presented in International desalination association world congress on desalination and water reuse, "the value of water in the 21st century," San Diego, USA, 29 August -3 sept. 1999
- [15] O.A. Hamed, A. M. Zamamiri, S. Aly and N. Lior, thermal performance and exergy analysis of a thermal vapor compression desalination, Energy Conversion Mgmt Vol. 37, No. 4, pp. 379-387, 1996
- [16] Karan H. Mistry and John H. Lienhard, Generalized least energy of separation for desalination and other chemical separation process, Entropy 2013, 15, 2046-2080
- [17] J. M. Veza, Mechanical vapor compression desalination plants-A case study, Desalination, 101 (1995) 1-10
- [18] Nafey A. S., Fath, H.E.S., Analysis of a new design of multi-stage flash-mechanical vapor compression desalination processes, desalination 204 (2007) 482-500