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Performance of One-Stage of Multi-Stage Flash System

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Abstract

One of the most extensive desalination facilities, the multi-stage flash (MSF) system uses saltwater to create desalinated water, which is then utilized to develop high productivity fresh (sweet) or non-salt water. The operation of MSF plants is depending on using thermal energy to evaporate some vapor (pure water) from the seawater based on the reduction in the operating pressure, which the generated vapor will condense to form the product. This article will outline the design of the brine heater and the one-stage (just the first stage) MSF system. The thermal performance (MSF plant efficiency) of the suggested system (one-stage of MSF), measured by Gain Output Ratio, reaches 0.45 (very low value). Therefore, the MSF plants must be designed with multi-stages to increase its thermal performance. A parametric study has been done to study the effect of tube length and vapor temperature on the number of tubes.

Keywords

Multi-stage flash, Multistage Flash Distillation, Multiple Effect Distillation, Vapor Compression Distillation, Reverse Osmosis

Introduction

Water is the foundation of all living creatures, for a being cannot live without water. Our planet's surface is made up of 70% water. Yet a shortage of clean drinking water plagues many countries. Even though a major portion of the earth is covered by water, there is a severe shortage of drinking water in most countries across the world. Safe drinking water is vital for all forms of life though it does not provide any calories. Desalination of seawater appears as a solution to this problem (Elimelech & Phillip, 2011). Desalination methods are categorized into thermal processes and membrane processes (Thimmaraju et al., 2018). The different thermal processes like Multistage Flash Distillation (MSF), Multiple Effect Distillation (MED), Vapor Compression Distillation (VCD), cogeneration and solar water desalination, and the membrane techniques (modern technology) such as Reverse Osmosis (RO) and Electro-dialysis/Electro-dialysis Reversal (ED/EDR) (Al-Othman, Tawalbeh, Assad, Alkayyali, & Eisa, 2018).

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State-of-the-art desalination processes that are applied to seawater and brackish water have proven to be effective in solving the issue (Mathioulakis, Belessiotis, & Delyannis, 2007). The following sections target modern desalination technologies and explain the options offered by them. Desalination methods are categorized into thermal processes and membrane processes. The different thermal processes like Multistage Flash Distillation (MSF), Multiple Effect Distillation (MED), Vapor Compression Distillation (VCD), cogeneration and solar water desalination, and the membrane techniques (modern technology) such as Reverse Osmosis (RO) and Electro dialysis/Electro-dialysis Reversal (ED/EDR) (Thabit et al., 2019).

The method of multi-stage flash distillation involves passing saline feed water through multiple chambers (stages) passing through one brine heater (Baig, Antar, & Zubair, 2011). To simulate MSF plants, several parameters are affected. These parameters are fluid temperature, pressure, and concentration on its thermal properties (El-Nashar, 1994). The water is heated and compressed to a high temperature and pressure in these stages. The pressure in the chambers gradually decreases as the water moves in, allowing the water to boil quickly. Boiling produces steam, which is freshwater, which is then concentrated and stored in each chamber, as shown in Figure 1. (Najafi, Alsaffar, Schwerer, Brown, & Ouedraogo, 2016). In this article, the design of a one-stage of MSF system, the thermal performance of the MSF system, the effect of tube length, and vapor temperature on the number of tubes are investigated.

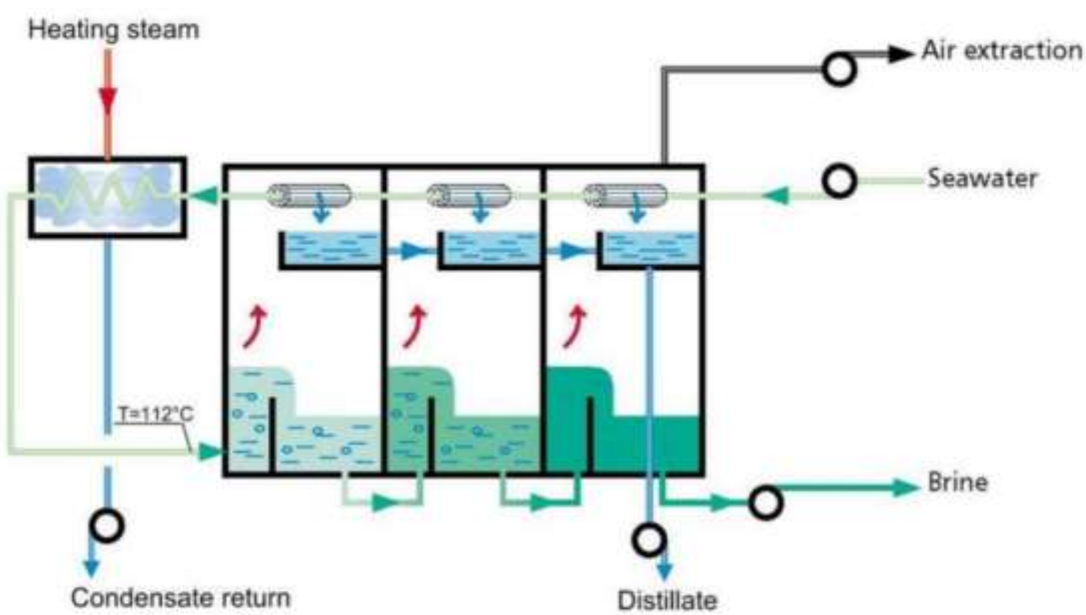

Figure 1. Conceptual diagram of MSF system (Najafi et al., 2016)

Methodology

The thermal performance of MSF plants is defined by the Gain Output Ratio (GOR) which is used to describe and/or measure the efficiency of the system (Hamed et al., 2000). As mentioned above, the suggested system consists of a one-stage and a brine heater. To solve the schematic diagram in Figure 2(a), we have to convert it into a physical model, as shown in Figure 2(b), to understand the interaction of the parameters. The Physical Model will describe the behavior of interactions of seawater in different parts of the MSF model including the distributions of mass, salt, and energy exchanges, as shown in Figure 2. In the brine heater, the warmed sweater will raise its temperature using an external heat source of steam then the heated seawater outlet is called feed water for the MSF stage. The feed water will flash into the chamber of the stage to produce a vapor and it will condense on the outer surface of the condenser to produce the distillate (condensate or freshwater), while the rest of the feedwater is called brine.

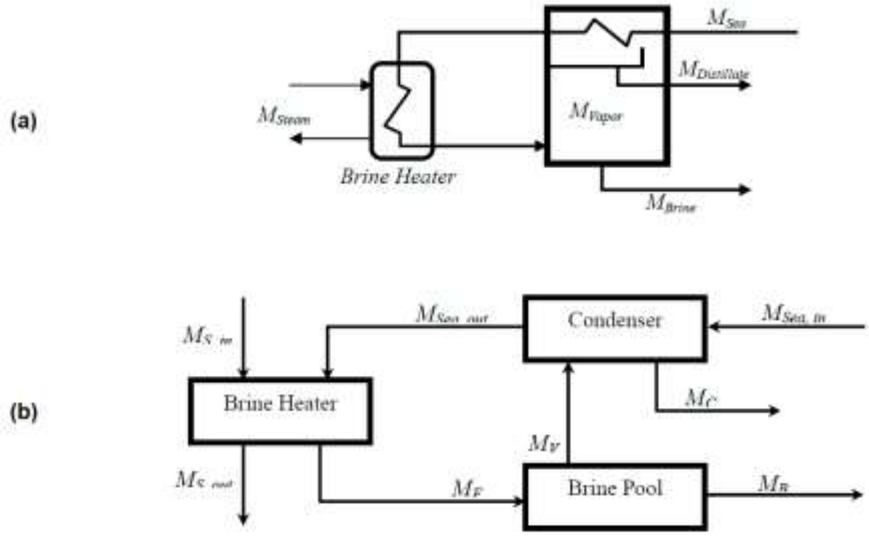

Figure 2. MSF methodology technique of brine heater and first stage; (a) schematic diagram, (b) physical model

Results and Discussion

An MSF system consists of a brine heater and 1st stage only, which is used a feed flow rate of 5513.8 kg/s (19850 t/hr). Using the plotting data on Figure 3 for Al-Taweelah MSF Plant in UAE, the top/maximum brine temperature (TBT) = 112 ^{o}C; heating steam temperature (T_s) = 120 ^{o}C; the feed temperature (T_{f1}) = 103.8 ^{0}C and the brine temperature in the 1st stage (T_b) = 108.2 ^{o}C. The following parameters are used as a constant value for simplification, such as salinity of feed water (S_F) 63000 ppm; the specific heat of water (Cp) = 4.18 J/Kg.^{o}C, and the overall heat transfer coefficient (U) = 3.5 kW/m^{2}.^{o}C. Assumed the length and diameter of the tubes for the flash chamber and brine heater are 3.0-m and 0.025-m, respectively.

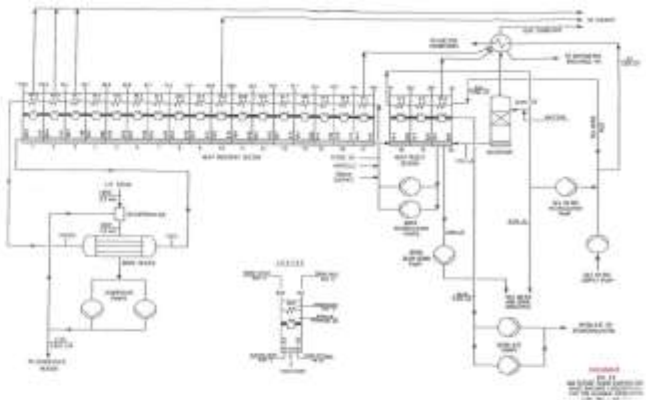

Figure 3. MSF desalination plant at Al-Taweelah site in UAE

Mass Balance:

For Condenser of 1st stage:

$$M_{Sea,in} = M_{Sea,out} = M_{Sea} = \frac{19850\ {}^{t}/_{hr} * 1000\ kg * 1\ hr}{3600\ s} = 5513.8\frac{kg}{s} \quad \text{(Given)}$$

$$M_V = M_C$$

For Brine Heater:

$$M_{Sea,out} = M_F = 5513.8\ kg/s$$

For Brine Pool in the 1st stage:

$$M_F = M_V + M_B$$

$$\therefore M_B = 5513.8 - 39.18 = 5474.62\ kg/s$$

Energy Balance:

For Condenser in the 1st stage:

$$M_V\, h_{fg} = M_{Sea}\, Cp\, (T_{Sea,out} - T_{Sea,in})$$

For Brine Heater:

$$M_S * h_{fg} = M_{feed} * Cp * (TBT - T_{F1})$$

$$\therefore M_s = \frac{5513.8 * 4.18\,(112 - 103.8)}{2201} = 85.8\ \frac{kg}{s}$$

For Brine Pool:

$$M_F\, Cp\, T_{TBT} = M_V\, h_{g,V} + M_B\, Cp\, T_B$$

$$M_v = \frac{5513.8 * 4.18 * 112 - 5474.65 * 108.2}{2687} = 39.18\frac{kg}{s}$$

The assumed overall heat transfer coefficient is 3.5 kW/m^2.ºC. The heat transfer area for Flashing Chamber (FC) can be calculated by the following equation:

$$A_{FC} = \frac{\dot{Q}_{FC}}{U_{FC}\, LMTD_{FC}}$$

$$LMTD_{FC} = \frac{(T_v - T_{f2}) - (T_v - T_{f1})}{\ln\left(\frac{T_v - T_{f2}}{T_v - T_{f1}}\right)} = \frac{(107.2 - 103.8) - (107.2 - 100)}{\ln\left(\frac{107.2 - 103.8}{107.2 - 100}\right)} = 5.064\ °C$$

$$\dot{Q}_{FC} = M_V\, h_{fg,V} = M_{Sea}\, Cp\, (T_{Sea,out} - T_{Sea,in}) = 39.15 * 2238 = 87617.7\ kW$$

$$\therefore A_{FC} = \frac{87617.7}{3.5 * 5.064} = 4943\ m^2$$

$$N_{fc} = \frac{4943}{3 * 0.025 * \pi} = 20979$$

While the heat transfer area of Brine Heater (BH) can be calculated by the following equation:

$$A_{BH} = \frac{\dot{Q}_{BH}}{U_{BH}\, LMTD_{BH}}$$

$$LMTD_{BH} = \frac{(T_s - T_{f1}) - (T_s - T_{TBT})}{\ln\left(\frac{T_s - T_{f1}}{T_s - T_{TBT}}\right)} = \frac{(120 - 103.8) - (120 - 112)}{\ln\left(\frac{120 - 103.8}{120 - 112}\right)} = 11.62\ ℃$$

$$\dot{Q}_{BH} = M_S\, h_{fg,S} = M_{Sea}\, Cp\, (T_{TBT} - T_{Sea,out}) = 85.8 * 2203 = 189017.4\ kW$$

$$\therefore A_{BH} = \frac{189017.4}{3.5 * 11.62} = 4647.5\ m^2$$

$$N_{BH} = \frac{4647.5}{3 * 0.025 * \pi} = 19724$$

Salt Balance:

For Brine Pool:

$$M_F * S_F = M_V * S_V + M_B * S_B$$

$$S_B = \frac{M_F * S_F}{M_B} = \frac{5513.8 * 63000}{5474.65} = 63451\ ppm$$

Engineering equation solver (EES)

As shown in Figure 4, the mass unit is converted from t / h to kg / s. The LMTD following is found by finding the enthalpy for the steam temperature from the steam table. Finally, the heat transfer for the brine heater "Qbh" is calculated by using the area of the brine heater.

Next, the calculation for the flash chamber is started as shown in Figure 5 using the vapor temperature; Tv gave then the enthalpy is gotten for the vapor from the steam table. Upcoming and as the BH was done, the LMTD is calculated, and using the equations mentioned before the area of the flash chamber is found and moved to the final step which is finding the GOR of the system.

```
//................ Inputs...........

Cp=4.18                "specific heat of water, J/kg.oC"

TBT=112                 "total brine temperature, C"
Ts=120                 "steam temperature in, C"
T_feed1=103.8
T_brine=108.2
S_feed=63000

Tube_length=3
Tube_length_bh=3
Tube_diameter=0.025
Tube_diameter_bh=0.025

U=3.5                  "overall heat transfer coefficient, kW/m^2.oC"

//........Brine Heater........
LMTD_bh=((Ts-T_feed1)-(Ts-TBT))/ln((Ts-T_feed1)/(Ts-TBT))        "logarithmic mean temperature difference, C"

Hg_Ts=enthalpy(Steam,T=Ts,x=1)           "from the steam table, kJ/kg"
Hf_Ts=enthalpy(Steam,T=Ts,x=0)           "from the steam table, kJ/kg"
Hfg_Ts=Hg_Ts-Hf_Ts

M_steam* Hfg_Ts=M_feed*Cp*(TBT-T_feed1)
M_steam_ton=M_steam*3.6

Qbh=M_steam*Hfg_Ts
Area_bh=Qbh/(U*LMTD_bh)
Area_bh=Nbh*Tube_length_bh*Tube_diameter_bh*Pi
```

Figure 4. Using EES to calculate the brine heater

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//.........Flash Chamber.....
Tv=107.2
Hg_Tv=enthalpy(Steam,T=Tv,x=1)          "from the steam table, kj/kg"
Hf_Tv=enthalpy(Steam,T=Tv,x=0)          "from the steam table, kj/kg"
Hfg_Tv=Hg_Tv-Hf_Tv

M_feed=19850/3.6                "mass, change t/h to kg/s"
Pv1=1.3                          "pressure, bar"
LMTD_fc=((Tv-T_feed2)-(Tv-T_feed1))/ln((Tv-T_feed2)/(Tv-T_feed1))    "logarithmic mean temperature difference, C"

Mc=Mv

M_feed*Cp*(TBT-T_brine)=Mv*Hfg_Tv
M_brine=M_feed-Mv
M_feed*S_feed=M_brine*S_brine
M_feed*Cp*(T_feed1-T_feed2)=Mv*Hfg_Tv
Qfc=Mv*Hfg_Tv
Area_fc=Qfc/(U*LMTD_fc)
Area_fc=Nfc*Tube_length*Tube_diameter*Pi

GOR=Mc/M_steam
```

Figure 5. Using ESS to calculate the flash chamber

As shown in Figures 6 and 7, the results of the above equations are plotted on the brine heater and 1st stage, in which the area and number of tubes bundle are 4646 m^2 and 19719 for the brine heater, while they are 4941 m^2 and 20970 for the condenser of the 1st stage, respectively. The calculated mass flow rates, temperatures, and salinity of different fluids are plotted, too. The calculated value of GOR reaches 0.46, which is considered a very low value. Therefore, the multi-stages must be considered in MSF design.

A parametric study has been done, which the effect of the length of the tube bundle on the number of tubes is presented in Figure 8a for the brine heater, while the number of tubes is calculated as a function of the temperature of the generated vapor for the condenser of the 1st stage, as shown in Figure 8b.

Figure 6. The results for the brine heater and flash chamber using EES software.

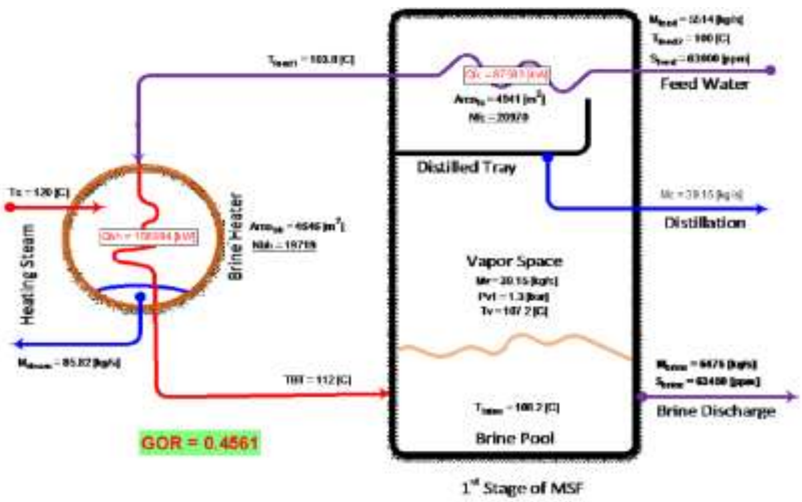

Figure 7. Results of design of the brine heater and the 1st stage

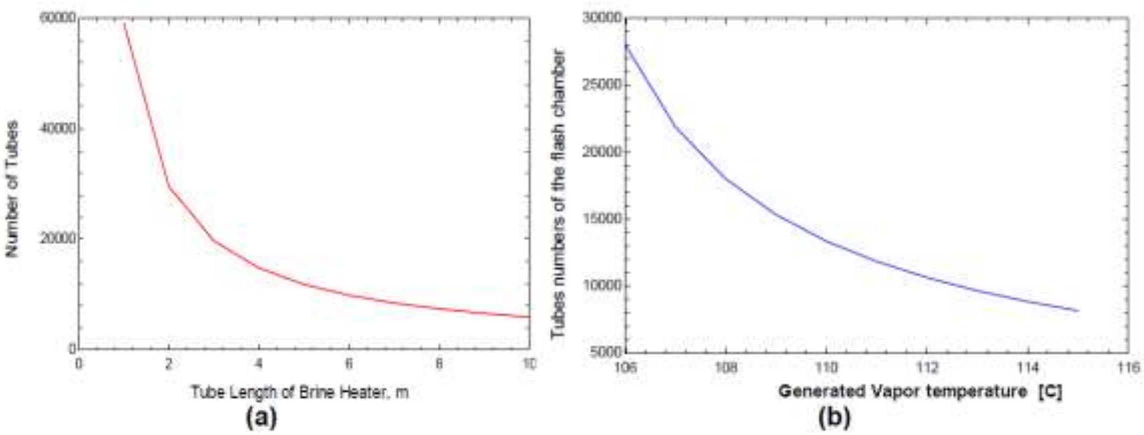

Figure 8. Calculation of number of the tube bundle in the brine heater and the condenser of 1st stage as a function of tube length and temperature of the generated vapor

Conclusion

This article described the one-stage MSF plant and calculates how the performance of this system can be efficient and economically safe. The system description and calculations of one stage and a brine heater are presented above. The calculated mass balance, energy balance, and salt balance are presented for the brine heater and 1st stage. Therefore, the conclusions include:

- The calculated thermal performance (GOR) of the one-stage MSF plant reaches 0.45 only, therefore the multi-stages system is suggested to recover the waste heat and increase its performance.
- Increasing the tube length and vapor temperature will decrease the number of tubes.
- The calculated number of tubes bundle of the brine heater and the condenser of 1st stage is 19724 and 20978, respectively, while the used diameter and length of the tube bundles are 1 inch and 3 m, respectively.

Acknowledgment

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