

THE SIMULATION OF A MULTISTAGE BRINE CONCENTRATION PROCESS WITH VERTICAL FALLING FILM EVAPORATION

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Abstract—Zero Liquid Discharge (ZLD) is a real process complex in terms of its design and operational control. The brine concentrating system can be considered as the most important component of ZLD processes. In the present study, mass and energy equations are written for a multistage brine concentrator unit with Feed Forward Multiple Effect Evaporation. Modeling of this process has been done, in which variable parameters are the number of stages, initial feed temperature, and the feed steam pressure. Parameters like the temperature of each stage, Gained Output Ratio (GOR), the required heat transfer area, the heat transfer coefficient, and other operational parameters are also calculated by the simulation code. The aim of this study is the investigation of the effect of key parameters on the performance of brine concentration process and on the process conceptual design.

Keywords—Brine Concentrator Unit, Vertical Falling film evaporator, Thermal Vapor Compression

I. INTRODUCTION

Considering the growth of the world population and, more importantly, the fast-growing development of industrial processes, there is a desperately growing need to high quality water. Out of 6.3 billion world inhabitants, 1.4 billion people live in arid areas that are dealing with a serious problem of water shortage. It is estimated that the number of people facing severe water shortage would reach 4 billion by the mid-twenty-first century. Therefore, the use of seawater, underground water reservoirs, waste and runny waters must be considered seriously (Stevens, 2003).

Regarding the importance of water production in different countries and areas nearby sea, many researches and studies have been done on various systems for providing sweet water in recent 50 years. These studies have intensified during the 10 last years, appearing novel methods such as ZLD process prospect. The waters whose minerals are unconventionally more than the standard limit for use are defined as waste waters in this paper. Current waters contain solutes such as NaCl, Ca(HCO₃)₂, MgSO₄, CaSO₄ and other salts. ZLD suggests that the process of reusing and recycling after treatment must be done in a manner that the output of the desalination process would be free of liquid water. One can mention the construction of a 750 MW power plant in a dry area in southern California, in which this

strategy has been done to overcome the problem of water shortage (Davis *et al.*, 1967)

Regarding the recent advent of ZLD systems, accurate and sufficient amount of information about these systems can hardly be found in today scientific sources. The majority of available data are related to conventional evaporators and concentrators, such as multistage distillation water units. As an example, Aly (1983) optimized for Forward Feed Multiple Effect Evaporation units using thermo-compressor. El-Dessouky and As-sassa (1985) investigated multi effect evaporators with thermal vapor compressor (MEE-TVC). They did a comparison between these systems and other thermal methods. Darwish and El Hadik (1986) presented a thermodynamic analysis of multi effect evaporators (MEE) based on physical properties of the system and calculating the required heat transfer area.

Tonelli *et al.* (1990) presented a calculation package for the simulation of multistage evaporators. The obtained results very similar to experimental results. Hanbury (1995) introduced a solution for governing equations of a Multiple Effect Desalination (MED) system in the steady state condition. Aly and Fiqi (2003) developed a mathematical model for MED units and investigated the impact of crucial parameters like first stage temperature, the number of stages and the fouling resistance on the heat transfer area of the system. Khademi and Rahimpour (2009) dealt with the simulation and optimization of multistage distillation system processes by solving mass and energy conservation equations in steady state condition and investigated the effect of process parameters including feed stream flow rate and its temperature along with the condenser pressure. They also optimized the unit from economic point of view using genetic algorithm. Investigation the performance of the unit experimentally, Park and Kim (2009) demonstrated that bent and striated tubes increase heat transfer. Their experiments showed a 5-10 times increase in heat transfer, in comparison with plain tubes. Using numerical method, Park and Kim (2009) suggested that when the feed water enters the tubes in saturated temperature, the system's efficiency increases. They also investigated the effect of thickness of dispersal film layer on heat transfer and on flow regime.

The majority of expert companies in the field of desalination and water treatment have delineated their future plans as attaining ZLD technologies. There are different methods and processes by which ZLD can be obtained. One of the most popular and convenient ZLD

processes consists of two types of equipments which are serially installed; one is Brine Concentrator (BC) and the other is crystallizer. The Brine Concentrator (BC) is usually a falling film evaporator. These evaporators generally operate in one-stage. But, for the sake of enhancing the economical and general efficiency, multi-stage utilization is preferred for larger capacities. The available commercial capacity of these evaporators can range from 10 – 700 gallons/minute. The brine concentrator is the most important part of this process as it is more complex and it has more critical design points, either from the viewpoint of process design or mechanical design, which should be considered in the design of these units.

In the present work, in addition to describing the operation and design procedure of a brine concentrator system, the effect of changing the operational and design parameters on process output variables and the performance of the system have been investigated.

II. PROCESS DESCRIPTION

The system of interest in this study is a multistage evaporator unit, which number of stages can be specified by as an input variable. As a high water recovery should be achieved in ZLD process, the brine is repeatedly concentrated in successive stages; so, forward feeding is used in this process. In other words, the effluent brine of each effect is mixed with the recycling flow of next effect and enters to the next effect as feed stream. In the brine concentrator, the brine enters the tubes of vertical falling film evaporators where it receives the required heat for evaporation from the steam flowing inside the shell. Thus, the water inside of tubes evaporates and the vapor outside of tubes condenses and forms film on the outer wall of vertical tubes moving downward. The condensate leaves the plant as distillate and a portion of the remaining part of concentrated feed is purged from the unit as brine stream. For the sake of saving cost and energy, the produced vapor inside the tubes of each stage is utilized in a subsequent stage as heating medium outside the tubes. The required steam in the first effect is provided by two sources. The first source is pressurized motive steam which is produced in boiler and another part is the low pressure vapor from the effluent of first effect which is sucked by thermocompressor. The function of the thermocompressor is to pressurize effluent steam of the first effect by a high pressure motive steam so as it can enter the first effect again. Using thermocompressor, the motive steam consumption will be reduced as a portion of used steam in the first effect is provided using the low pressure sucked steam from the effluent of the first effect. A schematic view of the process is provided in Fig. 1.

For a ZLD process, the falling film evaporator is designed in such a way that operates within a low temperature difference between warm and cool fluid. In addition, the recirculation flow rate is high. In other words, a huge amount of concentrated feed is turned

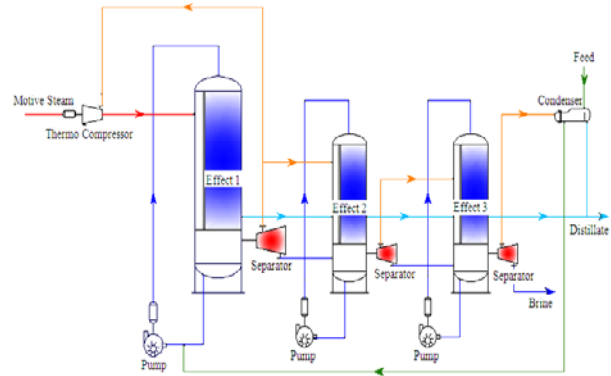


Figure 1. A schematic view of a three-stage brine concentrator with vertical falling film evaporator

back to the tubes. Meanwhile the fluid velocity is high in tubes to such an extent that it reaches 4-6 m/s in falling film evaporator. Such a high velocity of liquid streams inside the tubes is applied to avoid scaling and fouling of mineral salts inside the tubes. It should be noted that thermo-compressors are used in this unit so as to provide the entrained vapor with the produced vapor of one of the stages. Reviewing previous related works in literatures (El-Dessouky *et al.*, 1985; Khademi *et al.*, 2009; Kamali *et al.*, 2008), a program was written to estimate the overall heat transfer coefficient as accurately as possible.

III. MATHEMATICAL MODELING

A. Assumptions

Initially, it is assumed that the recovery of the whole unit is known. It has been proven that the area of multiple effect evaporators minimizes when a constant temperature difference between effects is applied. This is because if the effective temperature difference of an effect decreases noticeably, the area of that effect and the pressure drop increases in the same manner. It can be concluded that if the temperature difference is distributed equally in the MED plant, the pressure losses will be minimized and thus required area and fixed cost minimizes. Hence, it is assumed that there are equal differences between evaporator temperatures. Finally, the required steam for the thermocompressor is taken from the first effect. The entering steam temperature to the first effect and the condenser temperature are assumed as known variables.

B. Mass and energy balance of an evaporator

In Fig. 2, a schematic view of a vertical falling film evaporator is shown with its input and output streams. Equations of mass and energy conservation are written as follows:

$$W_{i-1} = W_i + V_i \quad (1)$$

In this equation, W (kg/s) is the output brine of each stage and V (kg/s) is the produced steam in each stage.

$$D_{i-1} + V_{i-1} = D_i \quad (2)$$

where, D is the steam flow which is condensed inside the shell and is summed up with produced steams of previous stages.

$$W_{i-1}x_{w_{i-1}} = W_ix_{w_i} \quad (3)$$

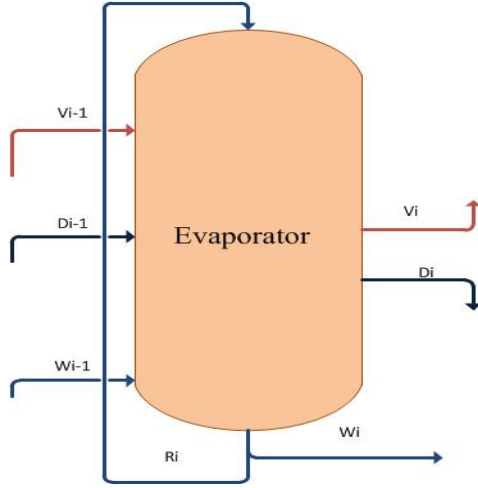


Figure 2. A schematic view of input and output flows of an evaporator

where, x is the concentration of liquid streams.

$$V_{i-1}H_{V_{i-1}} + D_{i-1}H_{D_{i-1}} + W_{i-1}H_{W_{i-1}} = V_iH_{V_i} + D_iH_{D_i} + W_iH_{W_i} \quad (4)$$

where, H denotes the stream enthalpy.

$$V_{i-1}\lambda_{i-1} = U_i A_i \Delta T_i \quad (5)$$

In the above equation, λ (KJ/kg) is the latent heat of evaporation, A (m^2) is the heat transfer area of each stage, ΔT ($^{\circ}C$) the temperature difference between stages, and U (KW/ m^2K) is the overall heat transfer coefficient of each stage.

$$\frac{1}{U} = \frac{\left(\frac{d_o}{d_i}\right)}{h_i} + \left(\frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2k}\right) + R_f + \frac{1}{h_o} \quad (6)$$

where h_i (W/ m^2K) denotes the heat transfer coefficient inside tube, h_o (W/ m^2K) is the heat transfer coefficient outside tube, R_f (m^2K/W) represents the precipitation resistance, k (W/ mK) is the thermal conductivity coefficient, d_i and d_o (m) denote the inner and outer diameter of the evaporator tube (m), respectively.

$$T_{v_{in_i}} = T_{v_{out_i}} - \Delta T_{friction_i} - BPE_i \quad (7)$$

where T_b ($^{\circ}C$) is the brine temperature, $T_{v_{out}}$ ($^{\circ}C$) is the temperature of produced steam in the effect, which is in thermal equilibrium with the brine stream, $\Delta T_{friction}$ ($^{\circ}C$) is temperature drop due to frictional pressure drop and BPE ($^{\circ}C$) is boiling point elevation due to presence of dissolved solids in boiling liquor in each effect.

C. Mass and energy balances for the brine collector

The mass and energy equations for the brine collector are as follows:

$$R_i = L_i + V_i \quad (8)$$

where R (kg/s) is the reverse flow of each stage and L (kg/s) is the liquid output flow of tubes.

$$R_i = \alpha_i W_{i-1} \quad (9)$$

where α_i is the reflux ratio, which is the mass ratio of reverse flow of the effect to the input brine from last effect.

Table 1. Assumptions and results of the brine concentrator design

	1 st stage	2 nd stage	3 rd stage
used steam flow rate (ton/h)		30.1	
Feed flow rate (ton/h)		151.2	
Input solute concentrations (g/l)		17	
Total recovery (%)		75.4	
Boiler vapor pressure (kPa)		2300	
Brine flow rate (ton/h)	95	67.3	37.2
Pressure (kPa)	31.2	21.4	14.3
Temperature ($^{\circ}C$)	70	61.6	53
Boiling Point Elevation ($^{\circ}C$)	0.39	0.53	0.97
Brine concentrations (g/l)	27.063	38.184	69.106
reverse flow concentrations (g/l)	27.063	38.184	69.106
Output liquid of tubes (g/l)	33.004	46.565	84.275
Heat transfer area (m^2)	2907	1019	1191
Recovery of each stage (%)	37.184	29.124	44.746
Reflux ratio	2.066	1.618	2.486

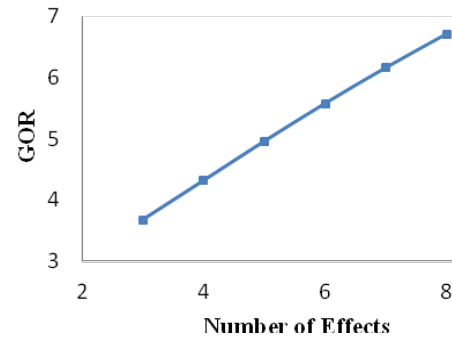


Figure 3. The relationship between number of stages and GOR

$$M_i = L_i + W_{i-1} \quad (10)$$

$$M_i x_{M_i} = W_{i-1} x_{w_{i-1}} + L_i x_{L_i} \quad (11)$$

$$L_i H_{L_i} + D_{i-1} H_{D_{i-1}} + W_{i-1} H_{w_{i-1}} = R_i H_{R_i} + D_{i-1} H_{M_i} + W_i H_{w_i} \quad (12)$$

$$D_i H_{D_i} = V_{i-1} H_{v_{i-1}} + D_{i-1} H_{M_i} \quad (13)$$

where H_f (KJ/kg) is the enthalpy of saturated liquid in a certain temperature.

These equations solved simultaneously by Newton-Raphson method for the solution of set of nonlinear equations.

IV. RESULTS AND DISCUSSION

Table 1 presents the specifications and some of design assumptions of a case study of a brine concentrator unit.

A. The relationship between Gained Output Ratio and the number of stages

Gained Output Ratio is defined as the net product flow to the consumed vapor ratio and is a very important parameter in the evaluation of performance of brine concentrator units. Higher GOR value indicates higher production of distillate water per unit of motive steam consumption or in other words higher energy efficiency. The relationship between the Gained Output Ratio and the number of stages can be seen in Fig. 3. By increasing the number of stages from 3 to 8, the Gained Output Ratio will reach as much as 6.71 in a 8-stage unit. In other words, for a certain amount of product, an increase in number of stages reflects in a decrease in used

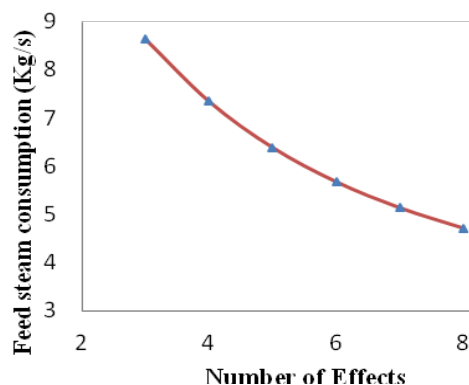


Figure 4. Feed vapor flow versus number of stages

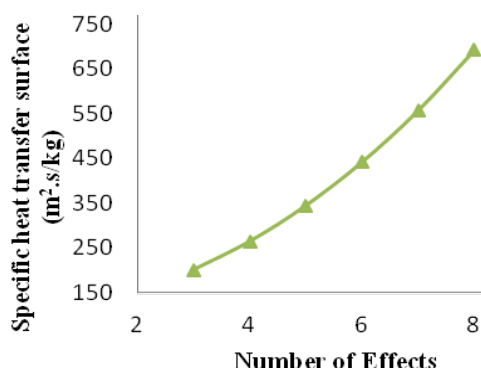


Figure 5. Specific heat transfer area versus number of stages

steam. It must be considered that this diagram is drawn assuming that the temperature of entering steam to the first effect is fixed at 70 °C and the condenser temperature is fixed at 45 °C. The temperature of all effects and required surface area for the desalination unit is calculated based on overall temperature difference of the unit and calculated pressure losses for each effect.

Figure 4 demonstrates that by enhancing number of stages from 3 to 8, the amount of used vapor declines (the minimum amount is 4.72 kg/s in 70 °C).

As shown in Fig. 5, there is a direct relationship between the number of stages and the required specific heat transfer area. The specific area parameter is obtained by dividing the required total heat transfer area by the unit product flow rate. Specific surface area indicates the amount heat transfer surface area per unit of product flow rate or in other words, the amount of fixed cost spent per unit of product flow. Lower specific area indicates less expensive brine concentration unit with respect to its capacity.

B. The effect of entering vapor to the first stage

The impact of vapor pressure on the required area for heat transfer

It is expected that by elevating the vapor pressure at the inlet of the first stage, the required heat transfer area will diminish. Because, according to Eq. 5, an increase in pressure reflects in an increase in temperature difference between the vapor and the brine. Altogether, if the transferred heat is constant, the overall areas will dimin-

ish by increasing temperature difference across brine concentration unit. Fig. 6 demonstrates that the current modeling meets this expectation. As it can be observed, an increase in vapor pressure has resulted in a reduction in specific heat transfer area. As the entering vapor to first effect is saturated vapor, an increase in the pressure of the stream is equivalent to increase in the steam temperature and thus higher temperature difference of desalination unit. But these changes are not linear, for increasing temperature difference has stronger effect on calculated surface area when the temperature difference is small. In this situation rising the temperature of steam and thus overall temperature of unit sharply increases the effective temperature difference of the unit and so specific surface area considerably decreases. While when steam temperature and overall temperature difference of the unit is high enough, further increasing of the steam temperature has smaller influence on calculated surface area.

Figure 6 illustrates the variations of the specific heat transfer area versus vapor pressure for 4 to 8-stage units. At lower pressures of feed steam, the difference among required specific areas is remarkable (the required specific area for a 4-stage unit is 359.23 m².s/kg and for an 8-stage unit is 1037.2 m².s/kg). As the pressure is further enhanced, this difference tends to lessen (the overall required area for a 4-stage unit is 208.8 m².s/kg and for a 8-stage one is 507.56 m².s/kg). It should be noticed that as the concentration of the total dissolved solids in the last effect of desalination unit is about 70 gr/lit, the BPE of the last stage is about 1.5 °C and so operating of desalination units having up to 8 stages is feasible.

The impact of vapor pressure on GOR

The variations of GOR with the output vapor pressure of thermo-compressor for 4- stage to 8-stage units are illustrated in Fig. 7. It can be concluded that GOR is not highly dependent on feed vapor pressure. Nevertheless, this dependence intensifies as the number of stages increases. It shows that the development of vapor pressure in units with more stages can further reduce the amount of vapor consumption.

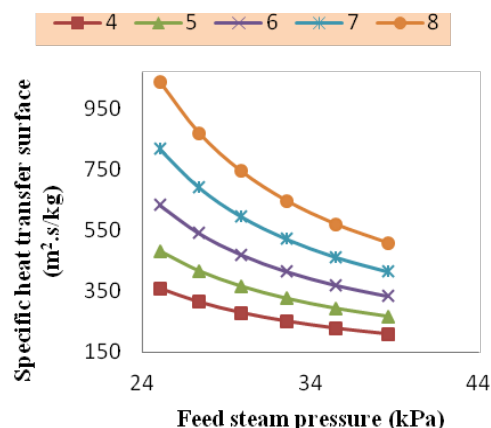


Figure 6. Specific heat transfer areas versus vapor pressure for different number of stages

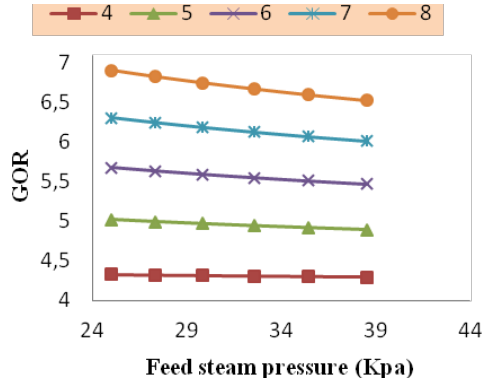


Figure 7. GOR versus the output vapor pressure of thermo-compressor for different number of stages.

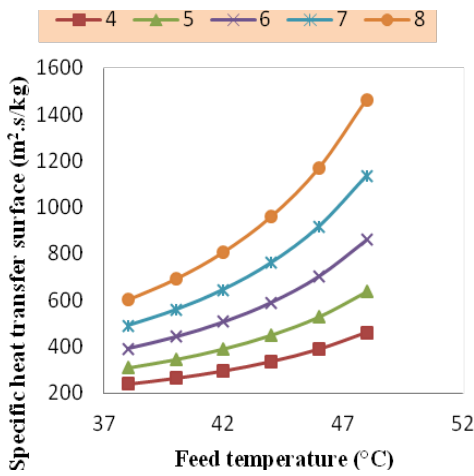


Fig. 8. Specific heat transfer area versus feed temperature for different number of stages.

C. The impact of feed temperature (water feed)

The feed temperature is influential in many ways. The dependence of the solubility of feed impurities is the first aspect. As the temperature goes up, the solubility of most of the dissolved salts in water declines, as their solution is exothermic. Therefore the scaling rate on evaporating tubes intensifies by increasing the temperature. Scaling is a major problem in the brine concentration units. In this paper, the details relating the calculation of sedimentation have been renounced for the sake of describing the process more concisely.

The other aspect is its impact on energy consumption and on costs which has been investigated through following sections.

The impact of feed temperature on the required heat transfer area

As it can be seen from Fig. 8, the larger the feed temperature, the larger the required heat transfer area will be. Increasing feed temperature has two opposite effects. Firstly, addition of the feed temperature reduces the required energy for evaporation of the feed and thus reduces heat load and specific surface area of the unit to some extent. Secondly, increasing feed temperature leads to an increase in the condenser temperature (as

approach temperature is assumed to be constant in the condenser of the unit) and therefore leads into the reduction of overall temperature difference across the brine concentration unit. The negative effect of reducing overall temperature difference overbears the positive effect of higher enthalpy of feed flow and hence the specific surface area tends to increase by rising of the feed temperature. The main responsible factor for the development of overall heat transfer area is the reduction in temperature difference (particularly in the first stage).

The impact of feed temperature on GOR

Figure 9 demonstrates that as the feed temperature increases, the GOR enhances as well. This is an expected result, for increasing the feed temperature reduces the required sensible heat which is needed to convert the sub cooled feed to saturated liquid. Therefore, the heat load of the effects will decrease and the required vapor as heating medium will consequently decrease. Therefore, the GOR enhances.

IV. CONCLUSIONS

In this paper, a multistage brine concentrator unit with thermo-compressor was modeled. The impact of different parameters such as feed vapor pressure and feed temperature on the specific heat transfer area and on energy efficiency, expressed in the term of GOR value, was investigated. It was observed that as the feed vapor pressure increases, the required surface area and GOR decrease, while by enhancing the feed temperature, these values intensify. Moreover, an increase in the number of stages had resulted in enhancement of GOR, which indicates higher energy efficiency. However, addition of extra effects to desalination unit resulted in higher required surface area for desalination unit showing higher fixed cost. Analysis of process variable parameters on GOR and specific area of the brine concentrator units can help to modify process condition so as to minimize fixed and variable costs of these units as the key part of zero liquid discharge systems.

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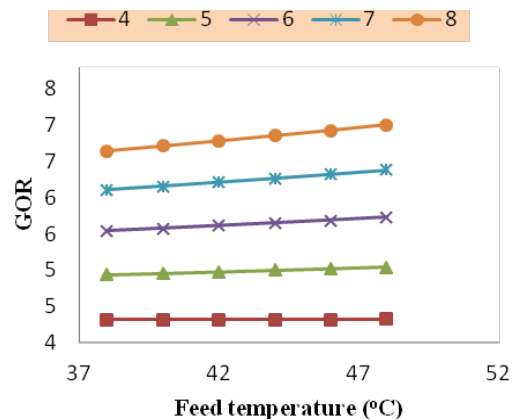


Figure 9. Variations of GOR versus feed temperature

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