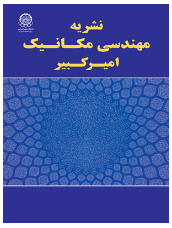

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Simulation of a Forced Multiple Effect Brine Concentration Process

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ABSTRACT: Brine Concentration is a comprehensive process and has an effective role in reducing environmental pollution due to desalination plant wastewater. In this study, the equations, for feed-forward forced convective falling film brine concentrators, with the desired number of effects and thermal vapor compression have been solved by MATLAB code. Thermodynamic modeling results of a two stage brine concentrator represented that 6.25 ton/hr feed with 90000 ppm concentration produces 5 ton/hr fresh water and 1.25 ton/hr wastewater with 450000 ppm concentration. The gained output ratio of plant is 2.63 and the specific heat transfer area is 74.3 m2s/kg. Also, by thermohydraulic modeling, to control the sediment rate with the limitations of allowable pressure drop and stream velocity in different tube lengths and diameters and evaporator number of passes, heat transfer area and the number of tubes have been calculated. Finally, the effects of design variables on gained output ratio and specific heat transfer area are investigated. The results represented that effects number, feed, and driving steam temperature are the three most important variables since increasing the effects number causes a 17% increase in gained output ratio and 23.5% increase in the specific heat transfer area. Increasing 1 ̊C in feed and motive vapor temperature lead to a 2.5% increase and 3% decrease in the specific heat transfer area. But these two don’t have any effect on gained output ratio.

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1- Introduction

In recent years, population rapid growth and industrial development have led to an increasing need for fresh water.[1] With global desalination capacity, waste water of desalination plants has become an environmental threat. The number of water resources with the strict rules on effluent streams of industrial units has led to more emphasis on the process which has higher recovery. A sustainable method for brine treatment is to develop a Zero Liquid Discharge (ZLD) process, which is consists of Multiple Effect Distillation (MED) and evaporative crystallization [2]. This process concentrates brine with a high rate of salinity in order to get salt cake and more fresh water from the brine.

Researchers investigate the feasibility of promoting conventional desalination system to the ZLD process. Sagharichiha et al. [1] represented thermohydraulic modeling for a feed forward multiple effect evaporators and investigated the effects of different design variables on Gained Output Ratio (GOR) and Specific Heat Transfer Surface Area (SHSA). Najafi et al. [3] represented a thermo-economic evaluation of hybrid solar energy supply in a ZLD plant in the capital of Iran, Tehran city weather conditions based on the seasonal weather data. Azimibavil and Jafarian [4] studied seven remarkable evaporative heat transfer correlations and then a thermo-economic model of brine concentrator unit in the ZLD process was investigated. Chen et al.[2] conducted a thermodynamic analysis of the ZLD process to define the SHSA, specific heat consumption, and second law efficiency.

2- Process Description

The MED system consists of a number of evaporators and separators, a condenser, and a Thermo compressor for Thermal Vapor Compression (TVC). The main feed stream (F) that is brine from other desalination plants, is fed into the separator and then by a recycle flow (R_1), is divided into the tubes of the first effect. An external heat source steam called driving steam is directed to the shell side of the first effect to heat up and partially evaporate the feed. The produced vapor is divided into two streams. One is used as the heat source of the second effect and is directed to its shell side and another one is entrained by the Thermo compressor. While the unevaporated brine (W_1) at the bottom of the first effect constitutes the second effect feed. Shell side vapor is condensed and produces the first effect of fresh water (D_1). Each effect has a lower pressure than the previous one so that vapor from each effect can be condensed in the next effect. The condensation heat is transferred to the feed to induce evaporation. The last effect vapor is condensed in a condenser and the brine leaving the last effect is fed into the crystallizer.

In this study, a feed forward forced convective multiple

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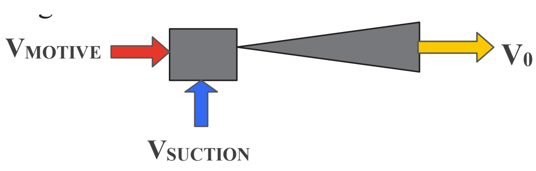

Fig. 1. Thermocompressor inputs and outputs flow

effects falling film brine concentrator with vertical tube is investigated. Compared with the other analyzes reported in the literature, this study contains more aspects of analyzing includes thermodynamic, thermohydraulic, and parametric study. Its novelty is to study the heat transfer area and tubes number of each effect in different tube lengths, diameters, and passes number with the limitations of allowable pressure drop and stream velocity in order to minimize the sediment rate.

3- Mathematical Modeling

The performance of the proposed ZLD process is evaluated via mathematical modeling. First, a process model is developed to access its thermodynamic efficiency and then the heat transfer area is studied by thermohydraulic analysis. In order to achieve these goals, mass and energy balance and other auxiliary equations for various components are proposed. The most important assumption which is considered are as follows:

The equations are in steady state form.

Thermocompressor is located at the first effect.

Non Condensable Gases (NCG) and their effects are not considered.

The component heat losses are not considered.

A schematic diagram of the thermocompressor is shown in Fig. 1.

Eqs. (1) and (2) represent entrainment ratio correlation and mass balance for thermocompressor.

$$ER = \frac{V_{SUCTION}}{V_{MOTIVE}} \quad (1)$$

$$V_{MOTIVE} + V_{SUCTION} = V_0 \quad (2)$$

A schematic diagram of the evaporator is shown in Fig. 2 and Eqs. (3) to (9) represent evaporators governing equations.

$$V_{i-1} + D_{i-1} = D_i \quad (3)$$

$$W_{i-1} = V_i + W_i \quad (4)$$

$$W_{i-1} x_{W_{i-1}} = W_i x_{W_i} \quad (5)$$

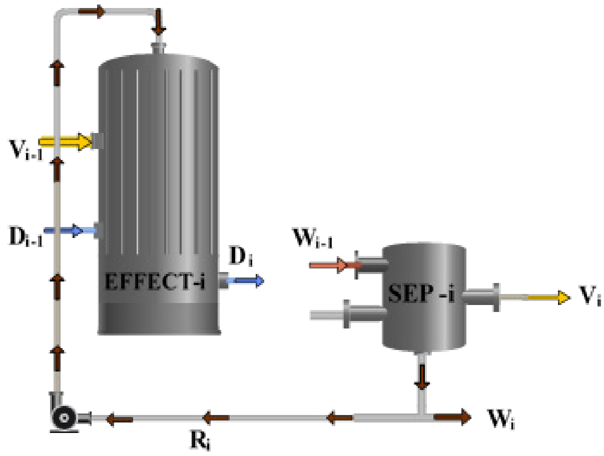

Fig. 2. Schematic of effects inputs and outputs flow.

$$V_{i-1} h_{V_{i-1}} + D_{i-1} h_{D_{i-1}} + W_{i-1} h_{W_{i-1}} = V_i h_{V_i} + D_i h_{D_i} + W_i h_{W_i} \quad (6)$$

$$T_{W_i} = T_{V_i} + BPE_i + \Delta T_{friction} \quad (7)$$

$$T_{V_{i-1}} - T_{W_i} - BPE_i - \Delta T_{friction} = \Delta T_i \quad (8)$$

$$PEP_i = \frac{V_i}{R_i} \quad (9)$$

Eqs. (10) to (13) represent other governing equations.

$$\beta = \frac{P}{F} \quad (10)$$

$$\beta = \frac{x_{W_n} - x_F}{x_{W_n}} \quad (11)$$

$$\left(V_n - V_c^*\right) h_{V_n} + D_n h_{D_n} - \left(V_n + D_n\right) h_{D_c} = M_{cw} \left(h_{cw_{out}} - h_{cw_{in}}\right) \quad (12)$$

$$V_c^* h_{V_n} = F(h_{F_2} - h_{F_1}) \quad (13)$$

4- Results and Discussion

The results of a two-effect plant are divided into three parts. The first one reports thermodynamic results which are mass flow rate, temperature, and concentration of different streams. It shows that 1.89 ton/hr motive steam is required for recovering 5 ton/hr fresh water from 6.25 ton/hr feed. So

Table 1. Results validation table

parameter	present work	(A&J)[4]	ξ%
Driving steam	2.98	2.97	0.3%
Feed	10.71	10.71	0.0%
Cooling water	68.61	79	13.1%
Motive vapor	1.85	1.78	3.8%
TVC suction	1.13	1.09	3.5%
GOR	3.64	3.55	2.5%
Product temp.	52	50	3.8%
Brine	[8.6 6.3 3.9]	[8.6 6.3 3.9]	0.0%
Distilled water	[2.9 5.1 7.3]	[2.9 5.1 7.3]	0.0%
Vapor	[2.1 2.2 2.3]	[2.1 2.2 2.3]	0.0%
Recycle	[53 56 59]	[53 56 58]	0.8%
Brine temp.	[67 61 54]	[67 61 53]	1.4%
Brine concentration	[0.1 0.15 0.24]	[0.1 0.15 0.24]	0.0%

the GOR value of this plant is 2.63. Also, distilled fresh water mass flowrate increase 42%, brine stream decrease 55%, and salinity of brine increased 125% when they pass through the effects.
The results have also been validated with that reported by Azimibavil and Jafarian (A&J) [4] as Table 1. In this table, flowrate values are in ton/hr and temperature values are in ˚C. The last column ξ represents the error percentage.

The second part is thermohydraulic results which report heat transfer area and tubes number of each effect and condenser in different tube lengths and diameters with the limitation of allowable pressure drop and stream velocity. In 1” constant tube diameter, increasing tube length from 3m to 4m leads to 42.3% and 54.7% increase in stream velocity and pressure drop and 7.4% and 30.5% decrease in heat transfer area and tubes number. Also in the 4m constant tube length, increasing tube diameter from 1” to 1.25” leads to a 27.9% decrease in stream velocity, 16.9% decrease in pressure drop, 12.8% decrease in the number of tubes, and 9.6% increase in the heat transfer area. So the SHSA value of this plant is 74.3 m^2s/kg.
Finally, a parametric study is conducted to investigate the influences of design variables on GOR and SHSA values. The important results of this part are as follows:
Variation of effect number by one leads to a 17% increase in GOR and a 23.5% increase in SHSA value.
1 ˚C feed temperature rising leads to 2.5% increase in SHSA but its effect on GOR value is ignorable.
Increasing 1 ˚C in driving steam temperature leads to a 0.1% decrease in GOR and 3% in SHSA value.
Increasing feed salinity by 1% leads to a 0.5% decrease in GOR value and a 0.3% increase in SHSA.
A 10% increase in recovery ratio (β) leads to a 1.5% increase in GOR value but the effect on SHSA is ignorable.
Increasing the thermocompressor entrainment ratio by 0.1 leads to a 3.5% increase in GOR value.

5- Conclusion

This study focused on mathematical modeling of multiple effect brine concentrator systems with vertical tube falling film evaporators as the main part of the ZLD process. A thermodynamic analysis was first performed to calculate the mass flow rate and temperature of different streams and then calculate the GOR value as an important result of the present work. In the second step, thermohydraulic analysis was conducted to investigate the influences of tubes diameter and length on heat transfer area and number of tubes and then calculate the SHSA as another important result of this study. Finally, the parametric study was conducted and shows that the number of effects, feed, and driving steam temperature are the three most important design variables of all and have a key role in plant performance.

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