Simulation of a forced multiple effect brine concentration process

Abbas Forouzi Feshalami\textsuperscript{a}, Ramin Kouhikamali\textsuperscript{b}

\textsuperscript{a} MSc. Student, Guilan University/ Faculty of Mechanical Engineering
\textsuperscript{b} Associate Professor, Guilan University/ Faculty of Mechanical Engineering

ABSTRACT

Brine Concentration is a comprehensive process and has an effective role in reducing environmental pollution due to the desalination plant wastewater. In this study, the equations, for feed-forward forced convective falling film brine concentrators, with 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 m\textsuperscript{2}/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 17% increase in Gained Output Ratio and 23.5% increase in Specific heat transfer area. Increasing 1 C in feed and motive vapor temperature lead to 2.5% increase and 3% decrease in Specific heat transfer area. But these two don’t have any effect on Gained Output Ratio.

KEYWORDS

Brine Concentrator unit, Falling film evaporator, Thermodynamic and thermohydraulic design, Forced convective flow

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 amount of water resources with the strict rules on effluent streams of industrial units have led to more emphasis on process which have 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 high rate of salinity in order to get salt cake and more fresh water from brine.

Researchers investigate the feasibility of promoting conventional desalination system to ZLD process. Sagharichiha et al.[1] represented a 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 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 ZLD process was investigated. Chen et al.[2] conducted a thermodynamic analysis of 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 thermocompressor for Thermal Vapor Compression (TVC). Main feed stream (F) that is brine from other desalination plants, is fed into the separator and then by a recycle flow (R1), 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 to two stream. One is used as the heat source of the second effect and is directed to its shell side and another one is entrained by thermocompressor. While the unevaporated brine (W1) at the bottom of the first effect constitutes the second effect feed. Shell side vapor is condensed and produces the first effect fresh water (D1). Each effect has a lower pressure than 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 effect falling film brine concentrator with vertical tube is investigated. Comparing 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

Performance of the proposed ZLD process are 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 component are proposed. The most important assumption which are considered are as following:

- 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 thermocompressor is shown in Figure 1.

![Figure 1. Thermocompressor inputs and outputs flow](image)

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

\[ ER = \frac{V_{\text{Suction}}}{V_{\text{Motive}}} \]  
\[ V_{\text{Motive}} + V_{\text{Suction}} = V_0 \]  

A schematic diagram of evaporator is shown in Figure 2 and Equation (3)-(9) represent evaporators governing equations.

![Figure 2. Schematic of effects inputs and outputs flow](image)

\[ V_{i-1} + D_{i-1} = D_i \]  
\[ W_{i-1} = V_i + W_i \]  
\[ W_{i-1} x_{w_{i-1}} = W_i x_{w_i} \]  
\[ V_{i-1} h_{i-1} + D_{i-1} h_{D_{i-1}} + W_{i-1} h_{w_{i-1}} = V_i h_i + D_i h_D + W_i h_W \]  
\[ T_{W} = T_v + BPE_i + \Delta T_{\text{friction}} \]  
\[ T_{V_i} - T_{W_i} - BPE_i - \Delta T_{\text{friction}} = \Delta T_i \]  
\[ P_{EP} = \frac{V_i}{R_i} \]  

Equation (10)-(13) represent other governing equations.

\[ \beta = \frac{P}{F} \]  
\[ \beta = \frac{x_{w_i} - x_{F}}{x_{w_i}} \]  
\[ (V_v + V_i) h_i = (V_v + D_i) h_D + M_i (h_{w_i} + h_{w_{i-1}}) \]  
\[ V_i h_i = R(h_{F_i} - h_{F_{i-1}}) \]

4. Results and Discussion

The results of a two-effect plant are divided to three part. 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 the GOR value of this plant is 2.63. Also, distilled fresh water mass flow rate increase 42%, brine stream decrease 55% and salinity of brine increase 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, flow rate values are in ton/hr and temperature values are in C. The last column $\xi$ represents error percentage.

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

The second part is thermo hydraulic 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 27.9% decrease in stream velocity, 16.9% decrease in pressure drop, 12.8% decrease in number of tubes and 9.6% increase in heat transfer area. So the SHSA value of this plant is 74.3 m$^2$/kg.

Finally, parametric study is conducted to investigate the influences of design variables on GOR and SHSA value. The important results of this part are as following:

- Increasing 1 C in driving steam temperature leads to 0.1% decrease in GOR and 3% in SHSA value.
- Increasing feed salinity by 1% leads to 0.5% decrease in GOR value and 0.3% increase in SHSA.
- 10% increasing in recovery ratio (β) leads to 1.5% increase in GOR value but the effect on SHSA is ignorable.
- Increasing thermocompressor entrainment ratio by 0.1 leads to 3.5% increase in GOR value.

5. Conclusion

This study focused on a mathematical modeling of a multiple effect brine concentrator system with vertical tube falling film evaporators as the main part of the ZLD process. A thermodynamic analysis was first performed to calculate mass flow rate and temperature of different streams and then calculate the GOR value as an important result of present work. In 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 effect, feed and driving steam temperature are the three most important design variables of all and have a key role in plant performance.

References
