HEAT SAVING IN EVAPORATIVE CRYSTALLIZATION
BY INTRODUCING A HEAT PUMP

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ABSTRACT

In this work theoretical calculations had been made for suggested methods of heating mother liquor in a crystallizer for both kinds of evaporative crystallization process. These suggested designs aim to reduce and save the consumption of heat which leads to reducing operational costs for the two kinds of crystallization. It was found that in direct evaporative crystallization: when a heat pump was added to heat the medium (hot air), it had saved energy consumption range between 81 % to 93 % at different values of coefficient of performance (COP). In the second type - indirect evaporation, when a heat pump was added on line containing the mixture of vapor from crystallizer and steam from jacket outlet, this mixture becomes a heat source to the heat pump in order to preheat the inlet steam to the jacket. Calculations of this suggested design showed that the saved energy consumption was 8 % to 26 % at different COP.

Keywords: evaporative crystallization, energy saving, heat pumps.

INTRODUCTION

Crystallization is a solid-liquid separation process in which mass transfer occurs of a solute from the liquid solution to a pure solid crystalline phase (process where solid particles are formed from a homogeneous phase) [1]. It is an important operation in the chemical industry as a method for purification and a method for providing crystalline materials in the desired size range. In an energy-conscious environment, crystallization can offer substantial saving as a method of separation when compared with distillation, though it must be recognized that it is more costly to effect cooling than providing heating [2]. In crystallization; equilibrium is attained when the solution or mother liquor is saturated [3]. Crystallizers can be conveniently classified in terms of the method used to obtain deposition of particles: by cooling a concentrated hot solution; by evaporating a solution; by adiabatic evaporation cooling [2-5].

The concerns of energy consumption and environmental pollution urge researchers to work on the development of clean energy and the utilization of waste energy. Sorts of novel technologies were developed and the achievements were patented. Among these patents, the heat pump system is one important topic. It utilizes the transformation between potential energy and thermal power energy to realize the performance of heat pumping and refrigeration. Usually in such processes, two zones are present: a cooling zone, where heat must be removed from the process, and a heating zone, where heat must be added to the process.

The utilization of heat pumps in various chemical technological processes is considered one of the promising methods for energy saving [6, 7]. To our knowledge, the utilization of a heat pump in a crystallizer has not been reported in details yet for the purpose of energy saving. This work presents a theoretical analysis of the technical feasibility and the potential use of a heat pump in the process of direct and indirect contact evaporative crystallization. Principle schemes of the process with
insulation of the heat pump and a throttling valve, are proposed and the corresponding calculations are performed.

THEORY

Yield and heat effects in a crystallization process

In most cases, the process of crystallization is slow and the final mother liquor is in contact with a sufficiently large crystal surface so that the concentration of the mother liquor is substantially that of a saturated solution at the final temperature in the process.

In such cases, it is normal to calculate the yield from the initial solution composition and the solubility of the material at the final temperature. If evaporative crystallization is involved, the solvent removed must be taken into account in determining the final yield.

The actual yield may be obtained from algebraic calculations or trial-and-error calculations when the heat effects in the process and any resultant evaporation are used to correct the initial assumptions on the calculated yield. The heat effects in a crystallization process can be computed by one of the following methods: A heat balance can be made in which individual heat effects such as sensible heats, latent heats, and the heat of crystallization can be combined into an equation for total heat effects. The second method is an enthalpy balance. The method can be realised when the total enthalpy of all leaving streams minus the total enthalpy of all entering streams is equal to the heat absorbed from external sources by the process.

In using the heat-balance method, it is necessary to make a corresponding mass balance, since the heat effects are related to the quantities of solids produced through the heat of crystallization. The advantage of the enthalpy-concentration-diagram method is that both heat and mass effects are taken into account simultaneously. This method has limited use because of the difficulty in obtaining enthalpy concentration data. This information has been published for only a few systems [3].

Direct and Indirect Contact Evaporative Crystallization

The two processes of direct and direct evaporation crystallization are used basically to separate mineral salts from their water solution, by partial evaporation using heating agents (hot air in the direct method and steam in the indirect one) to reach over saturation state as shown in Figs. 1 and 2. When the crystals appear in the crystallizer, the formed slurry concentrated solution (mother liquor with crystals) is removed and fed to a separator to isolate the crystals [3]. The vapor out from the crystallizer goes to the atmosphere.

This work is concentrated on studying of the feasibility of possible reduction in the heat demand for the process of direct and indirect contact evaporative crystallization by introducing a heat pump in the process. For both processes, a model of sodium chloride water solution was used as a feed solution to the proposed process with the aim of extraction of salts minerals and
production of pure desalinated water.

The introduction of a heat pump (closed cycle) is shown in Fig. 3. The initial air with a temperature \( T_o = 25^\circ C \) is heated to a desired temperature \( T_1 \) by directing the air through the condenser of the heat pump which is the heater of the crystallizer in our case (heater). At the outlet of the bubble column crystallizer the moisture content is removed by condensing through passing it over the cooled surface of the heat pump evaporator (cooler). As shown in Fig. 4, we use a heat pump system to achieve a coefficient of performance (COP) which enables us to have specific operating conditions for the process.

Material Balance for Direct Contact Evaporative Crystallization Process with Heat Pump

Fig. 1 shows a flow diagram of a direct contact evaporative crystallization process using hot air as contact phase with the solution. The process is carried out in a bubble column crystallizer. Air is heated usually by an electrical heater or by contacting with other heating agents. Hot air of a flow rate \( L \) is brought into contact with solution \( F \) with a temperature and concentration \( T_F, X_F \), respectively, in a bubble column causing the air to cool and some of the liquid to evaporate. The air temperature will decrease from \( T_1 \) at the inlet of the column to \( T_2 \) at the outlet. Consequently, the absolute and relative humidity will increase from \( \alpha_{A1}, \alpha_{R1} \) to \( \alpha_{A2}, \alpha_{R2} \) respectively. The enthalpy of air may remain constant if the contact in the bubble column is going under adiabatic conditions or it may change from \( H_1 \) at the inlet to \( H_2 \) at the outlet, if other cooling conditions are applied. Distilled water of amount \( W \) is obtained by dehumidifying the air in a condenser (the evaporator of heat pump). The formed slurry concentrated solution \( D \) is separated to crystal phase \( K \) and mother liquor \( M \).

The overall material balance is:

\[
F = K + M + L(\alpha_{A1} - \alpha_{A2}) \tag{1}
\]

The amount of evaporated solvent (water) is determined according to the difference of moisture content (air humidity) between the inlet and outlet as:

\[
W = L(\alpha_{A1} - \alpha_{A2}) \tag{2}
\]

Substituting Eq. (2) into Eq. (1):

\[
F = K + M + W \tag{3}
\]

Also from

\[
D = K + M \tag{4}
\]

Then Eq. 4 becomes

\[
F = D + W \tag{5}
\]

The balance on solute can be expressed as:

\[
FX_F = DX_D + WX_W \tag{6}
\]

where \( X_F, X_D, X_W \) are the salt concentrations in the feed, slurry concentration solution and condensate phases, respectively. Taking into account that evaporated water contains zero amount of solute \( X_W = 0 \), then equation
(6) becomes:

$$FX_F = DX_D$$

(7)

An expression for the amount of crystal phase as slurry can be obtained by solving Eq. (7)

$$X_D = \frac{FX_F}{D}$$

(8)

The amount of crystals formed can be calculated by knowing the efficiency of the separator.

**Heat Balance of Direct Contact Evaporative Crystallization with Heat Pump**

The proposed process consists of direct contact evaporative crystallization with a heat pump as shown in Fig. 3. The initial air with a temperature ($T_1$) is heated to a desired temperature ($T_2$) by directing the air through the condenser (heater). At the outlet of the bubble column crystallizer the moisture content is removed by condensing it when passing over the cooled surface of the evaporator. The amount of heat that must be added to the air is the same or less than the amount of heat that must be delivered by the heat pump in the condenser and can be calculated as:

$$Q_H = L(H_1 - H_o)$$

(9)

The evaporator energy balance is:

$$Q_L = L(H_3 - H_2) = LC_{par}(T_3 - T_2)$$

(10)

The measure of performance of a heat pump is expressed in terms of coefficient of performance $COP_{HP}$ defined as

$$COP_{HP} = \frac{Q_H}{W_{in}}$$

(11)

By applying energy parlance on the heat pump

$$W_{in} = Q_H - Q_L$$

or

$$Q_H = W_n + Q_L$$

(12)

An expression for the applied work can be obtained by solving Eq. (11) and Eq. (12) together:

$$W_{in} = \frac{Q_L}{(COP_{HP} - 1)}$$

(14)

**Economic Analysis for a Direct Contact Evaporative Crystallization with a heat pump**

To evaluate the feasibility of introducing a heat pump into direct contact evaporative crystallization, it is required to estimate the cost of heating for an ordinary system and compare it with a system that includes a heat pump. Depending on the operating conditions, i.e. the source of heating medium used in the heater to heat up the initial air, the total operating cost ($$/hr) can be estimated as:

$$E_S = Q_H \times D_S + E_{heater}$$

(15)

where $D_S$ is the price of heating source ($$/kJ) in case of using steam, $E_{heater}$ ($$/h) is the cost of heating agent used in the heater

$$E_E = Q_H \times D_E$$

(16)

where $D_E$ is the price of the heating source ($$/kWh) in case of using electricity.

The cost of the process with a heat pump consists only from the cost of the electrical power supplied to the compressor which is estimated as:

$$P_a = W_n \times \eta$$

(17)

where $P_a$ is the actual electrical power required for a compressor and $\eta$ is the overall efficiency of the compressor which ranges from 65 to 75% [8]. The operating cost ($$/hr) of the system with a heat pump is:

The resulting saving factor by introducing a heat pump to a system of direct contact evaporative crystallization is defined by:

$$S_E = (1 - \frac{E_{HP}}{E_{S,E}}) \times 100\%$$

(19)

where $E_{HP}$ is the total operating cost of the heat pump in ($$/hr) and $E_{S,E}$ in case of using steam or electricity, respectively.
Energy Recycling and Recovery in Case of Indirect Contact Evaporative Crystallization

For an indirect evaporative process we studied the feasibility to energy recovery process i.e. the outlet steam that exited from crystallizer and jacket that would normally be wasted, converting it into thermal energy by addition of a heat pump on outlet vapor line and steam in three designs:

The inlet to the evaporator is outlet vapor from the crystallizer (Fig. 5).

The inlet to the evaporator is outlet steam from the jacket (Fig. 6).

The inlet to the evaporator is a mixture of the outlet vapor from crystallizer and steam outlet from the jacket (Fig. 7).

In the three cases, the heat pump makes a closed system, the condenser of the heat pump is connected on the inlet steam line to make a preheating of the steam inlet of the jacket, then the steam complete the heating to the required temperature using heater with low pressure steam.

The recovery energy of indirect contact evaporative crystallization with a heat pump first suggested system for energy is shown in Fig. 5. The superheated steam with temperature ($T_2 = 150^\circ C$) is fed to the jacket to be cooled and to give the evaporator crystallizer the required heat to realize the crystallization state. The saturated steam out from jacket is at temperature $T=25^\circ C$. The vapor resulting by the crystallization process out of the crystallizer is at temperature almost $70^\circ C$. The outlet steam from the jacket is drawn to the evaporator of the heat pump. The condenser of heat pump acts as a preheating medium for the inlet of the jacket.

The recovery energy of indirect contact evaporative crystallization with a heat pump - the second suggested system for energy, is shown in Fig. 6. The superheated steam with temperature ($T_2 = 150^\circ C$) is fed to the jacket to be cooled and to give the evaporator crystallizer the required heat to realize the crystallization state. The saturated steam out from jacket is at temperature $T=25^\circ C$. The vapor resulting from the crystallization process out of crystallizer is at temperature almost $70^\circ C$. The outlet vapor from the crystallizer is drawn to the evaporator of the heat pump. The condenser of heat pump acts as a preheating medium for the inlet of the jacket.

The recovery of indirect contact evaporative crystall-
lization with a heat pump - the third suggested system for energy is shown in Fig. 7. The superheated steam with temperature \( T_2 = 150°C \) is fed to the jacket to be cooled and to give the evaporator crystallizer the required heat to realize the crystallization state. The saturated steam out from the jacket is at temperate \( T = 25°C \). The vapor resulting by the crystallization process out of the crystallizer is at temperature almost \( 70°C \). The two outlets from jacket and crystallizer are mixed and drawn to the evaporator of the heat pump. The condenser of the heat pump acts as preheating medium for the inlet of the jacket.

**Material Balance for the Indirect Contact Evaporative Crystallization Process by Adding a Heat Pump**

Fig. 7 shows a flow diagram of the indirect contact evaporative crystallization process by using superheated steam without contact phase with solution (through jacket). The process is carried out in an evaporative column crystallizer. Steam is heated first by the condenser of the heat pump and then heated by an electrical heater or by contacting with other heating agents to reach to a desired temperature \( (T_2) \). A superheated steam with a flow rate \( (S) \) is fed to the jacket that heats the solution \( (F) \) with a temperature and concentration \( T_F, X_F, \) respectively. In an evaporative column some of the liquid is evaporated and the steam cooled (the superheated steam temperature will decrease): the outlet steam from the jacket is mixed with the steam out from the crystallizer to give steam with a flow rate \( (V) \) and a temperature \( (T_4) \), this steam is fed to the evaporator of the heat pump. The temperature will decrease from \( T_4 \) at the inlet of the evaporator to \( T_5 \) at the outlet. This decrease in temperature releases a definite amount of heat \( Q_L \). At given COP and known amount of \( Q_L \), we can estimate the amount of heat \( Q_H \) used for preheating the steam inlet to the jacket by the condenser of the heat pump after which a complete heating by the electrical heater or by contacting with other heating agents to reach to \( T_2 \) can give the operating conditions to realize the crystallization state.

The overall material balance is:

\[
F = K + M + V_0 \quad (20)
\]

The balance on solute can be expressed as:

\[
FX_F = kX_k + M X_M + V_0 X_{vo} \quad (21)
\]

where \( X_F, X_k, X_M, X_{vo} \) are the salt concentrations in feed, crystal, mother liquor and vapor phase, respectively. Taking into account that evaporated water contains zero amount of solute \( (X_{vo} = 0) \), equation (21) becomes:

\[
FX_F = kX_k + M X_{Mo} \quad (22)
\]

The total material balance is:

\[
D = K + M \quad (23)
\]

The component material balance is:

\[
DX_F = KX_k + M X_M \quad (24)
\]

Then eq. (20) becomes

\[
F = D + V_0 \quad (25)
\]

The balance on solute can be expressed as:

\[
FX_F = DX_D + V_0 X_v \quad (26)
\]

An expression for the amount of crystal phase can be obtained by solving Eq. (25) and Eq. (26) together and as we know \( X_{vo} = 0 \) then:

\[
\frac{V_0}{F} = 1 - \frac{X_F}{X_D} \quad (27)
\]

The total steam fed to the evaporator of heat pump is:

\[
V = V_0 + S \quad (28)
\]

**Heat Balance for Indirect Contact Evaporative Crystallization with a Heat Pump**

By applying energy balance on the steam that is fed to the jacket

\[
Sh_2 - Sh_1 = V_0 H_{vo} \quad (29)
\]

and then \( S \):

\[
S = \frac{V_0 H_v}{h_2 - h_3} \quad (30)
\]

The amount of heat generated from the evaporator can be calculated as:

1 - if the inlet to the evaporator is steam \( V_0 \):
\( Q_L = Q_v = V_o (h_4 - h_3) \)  

(31)

2 - if the inlet to the evaporator is steam \( S \): 

\( Q_L = Q_{so} = S(h_4 - h_5) \)  

(32)

3 - if the inlet to the evaporator is steam \( V \) (\( S + V \)): 

\( Q_L = Q_s + Q_v \)  

(33)

The measure of performance of a heat pump is expressed in terms of coefficient of performance \( \text{COP}_{HP} \) defined as: 

\[ \text{COP}_{HP} = \frac{Q_H}{W_{in}} \]  

(34)

By applying energy balance on the heat pump 

\[ W_{in} = Q_H - Q_L \]  

(35)

and 

\[ Q_H = W_{in} + Q_L \]  

(36)

An expression for the amount of work can be obtained by solving Eq. (34) and Eq. (36): 

\[ W_{in} = \frac{Q_L}{(\text{COP}_{HP} - 1)} \]  

(37)

The expression for the amount of heat that required increasing temperature \( T_1 \) to \( T_2 \) using a heater (without a heat pump): 

\( Q_S = S(h_2 - h_3) \)  

(38)

The makeup amount of heat (using a heater) which must be added after the heat pump, \( Q_J \) can be calculated by: 

\( Q_J = Q_s - Q_H \)  

(39)

Economic Analysis for an Indirect Contact Evaporative Crystallization Process with a Heat Pump

To evaluate the feasibility of adding a heat pump compressor on the outlet steam line (from crystallizer) in evaporative crystallization, it is required to estimate the cost of heating for an ordinary system and compare it with a system that includes a heat pump. Depending on the operating conditions, i.e: the source of heating medium used in the heater to heat up the inlet steam temperature (fed to the jacket), the total operating cost \( ($/hr) \) can be estimated as:

\[ \Phi_S = Q_s \times D_s + \Phi_{heater} \]  

(40)

where \( D_s \) is the price of the heating source \( ($/kJ) \) in case of using steam, \( \Phi_{heater} \): ($/h) is the cost of heating agent used in the heater. The cost of the process with a heat pump consists only from the cost of the electrical power supplied to the compressor which is estimated as:

\[ P_a = W_{in} \times \eta \]  

(41)

where \( P_a \) is the actual electrical power required for a compressor and \( \eta \) is the overall efficiency of the compressor which ranges from 65 to 75 \% [8]. The operating cost \( ($/hr) \) of the electrical power supplied to the compressor is estimated as:

\[ \Phi_H = P_a \times D_e \]  

(42)

The operating cost \( ($/hr) \) of the heat that is needed after preheating from heat pump (heating make up) is estimated as:

\[ \Phi_J = Q_J \times D_s + \Phi_{heater} \]  

(43)

the total operating cost \( ($/hr) \) of the process with a heat pump on the outlet vapor line (from crystallizer) is summation of the cost of the electrical power supplied to the compressor and the cost of heating make up steam, which can be estimated as:

\[ \Phi_T = \Phi_J + \Phi_H \]  

(44)

The resulting saving factor by indirect contact evaporative crystallization is defined by:

\[ S_e = (1 - \frac{\Phi_T}{\Phi_s}) \times 100\% \]  

(45)

where \( \Phi_T \) the total operating cost of the added compressor on the outlet steam line (from crystallizer) in ($/hr) and \( \Phi_s \) the total operating cost ($/hr) without a heat pump.

RESULTS AND DISCUSSION

Case one: Direct Contact Evaporative Crystallization with a Heat Pump

In our study we use a heat pump system to make a relation between the coefficient of performance (COP)
and the initial temperature of the hot air fed to the crystallizer at constant humidity. Then by solving of this relation we can see the effect of introducing a heat pump on the operational energy saving in the process of direct contact evaporative crystallization. The followings assumptions are proposed:

1. Steady state, steady flow operation.
2. Potential and kinetic energy effects are negligible.
3. No chemical reaction.
4. Adiabatic compression efficiency is 0.7.
5. The price of electricity and low pressure steam for heating (LPS) are estimated to be 0.05 ($/kW h) and 3.17 × 10^{-6} ($/kJ) respectively, and the cost of heating agent used in the heater 0.33 $/kJ [7].

The used high-efficiency heat pump has COP of (2.3-5) in the heating mode [6].

The used basis for calculation is listed in Table 1.

The calculations of the heat accepted by the evaporator \( Q_L \), work input into heat pump \( W \), heat generated by condenser \( Q_H \), inlet air temperature \( T_1 \), mass flow rate of water \( W \), mass flow of slurry concentrated solution \( D \), slurry concentration \( X_D \) and air moisture content at

![Fig. 8. Relation between inlet air temperature to crystallizer and slurry concentration.](image)

### Table 1. Basis for calculations [1, 4].

<table>
<thead>
<tr>
<th>F</th>
<th>1000 kg/h</th>
<th>( X_f )</th>
<th>0.36</th>
<th>( \alpha_{A2} @ T_2 )</th>
<th>0.022 kg water/kg dry air</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_2 )</td>
<td>25°C</td>
<td>( \alpha_{R1} )</td>
<td>20 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_3 )</td>
<td>10°C</td>
<td>( \alpha_{R2} )</td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>600 kg/h</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2A. Material and energy results of direct contact evaporative crystallization with heat pump.

<table>
<thead>
<tr>
<th>COP</th>
<th>( Q_L ) (KJ/hr)</th>
<th>( W ) (KJ/hr)</th>
<th>( Q_H ) (KJ/hr)</th>
<th>( T_1 ) (K)</th>
<th>( W ) (Kg/hr)</th>
<th>( D ) (Kg/hr)</th>
<th>( X_D )</th>
<th>( \alpha_{A1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>9270</td>
<td>7130.8</td>
<td>16400.8</td>
<td>324.7</td>
<td>1.8</td>
<td>998.2</td>
<td>0.360649</td>
<td>0.019</td>
</tr>
<tr>
<td>2.5</td>
<td>9270</td>
<td>6180</td>
<td>15450</td>
<td>323.2</td>
<td>3</td>
<td>997</td>
<td>0.361083</td>
<td>0.017</td>
</tr>
<tr>
<td>3</td>
<td>9270</td>
<td>4635</td>
<td>13905</td>
<td>320.7</td>
<td>3.6</td>
<td>996.4</td>
<td>0.361301</td>
<td>0.016</td>
</tr>
<tr>
<td>3.5</td>
<td>9270</td>
<td>3708</td>
<td>12978</td>
<td>319.2</td>
<td>3.6</td>
<td>996.4</td>
<td>0.361301</td>
<td>0.016</td>
</tr>
<tr>
<td>4</td>
<td>9270</td>
<td>3090</td>
<td>12360</td>
<td>318.2</td>
<td>4.2</td>
<td>995.8</td>
<td>0.361518</td>
<td>0.015</td>
</tr>
<tr>
<td>4.5</td>
<td>9270</td>
<td>2648.6</td>
<td>11918.6</td>
<td>317.4</td>
<td>5.4</td>
<td>994.6</td>
<td>0.361955</td>
<td>0.013</td>
</tr>
<tr>
<td>5</td>
<td>9270</td>
<td>2317.5</td>
<td>11587.5</td>
<td>316.9</td>
<td>6.6</td>
<td>993.4</td>
<td>0.362392</td>
<td>0.011</td>
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The calculations of total operating cost without heat pump (heating by steam) $E_{Es}$, the total operating cost without a heat pump (heating by electricity)$E_{Ei}$, the total operating cost with heat pump $E_{Hi}$, saving factor based on electrical heating $S_{EE}$, and saving factor based on steam heating $S_{Es}$ are presented in Table 2B.

The relationship between the inlet air temperature and the slurry concentration is shown in Fig. 8. It can be seen that as the inlet air temperature decreases, the concentration of slurry increases. This can be understood by the fact that at constant flow, the humidity of air flow decreases by lowering temperature and then maximize the ability of air to carry out water from solution.

Figs. 9 and 10 show that increasing of the value of COP results in increasing of the concentration of the produced slurry. It can be explained by the fact that the relationship between COP and the temperature of inlet air is inversely proportional.

The calculations indicate that the saving factor increases in both cases by increasing the COP. A noticeable saving factor is ranged between 81 % to

<table>
<thead>
<tr>
<th>COP</th>
<th>Es ($/ hr)</th>
<th>Ei ($/ hr)</th>
<th>Hi ($/ hr)</th>
<th>S_{EE} ($/ hr)</th>
<th>S_{Es} ($/ hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>0.38199</td>
<td>0.227788</td>
<td>0.069327</td>
<td>69.5652</td>
<td>81.85114</td>
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<tr>
<td>2.5</td>
<td>0.378977</td>
<td>0.214583</td>
<td>0.060083</td>
<td>72.0000</td>
<td>84.14589</td>
</tr>
<tr>
<td>3</td>
<td>0.374079</td>
<td>0.193125</td>
<td>0.045063</td>
<td>76.6667</td>
<td>87.95374</td>
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<tr>
<td>3.5</td>
<td>0.37114</td>
<td>0.18025</td>
<td>0.03605</td>
<td>80.0000</td>
<td>90.28669</td>
</tr>
<tr>
<td>4</td>
<td>0.369181</td>
<td>0.171667</td>
<td>0.030042</td>
<td>82.5000</td>
<td>91.86262</td>
</tr>
<tr>
<td>4.5</td>
<td>0.367782</td>
<td>0.165536</td>
<td>0.02575</td>
<td>84.4444</td>
<td>92.99857</td>
</tr>
<tr>
<td>5</td>
<td>0.366732</td>
<td>0.160938</td>
<td>0.022531</td>
<td>86.0000</td>
<td>93.85621</td>
</tr>
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</table>
93% and 69% to 86% based on electrical and steam heating, respectively. The results are shown in Figs. 11 and 12.

**Case Two: Adding a heat pump on the outlet vapor line from the crystallizer**

The aim of this construction is to utilize and recover heat content of the system by adding a heat pump in three cases:

1. If the inlet to the evaporator (of heat pump) is outlet vapor from the crystallizer.
2. If the inlet to the evaporator is outlet steam from the jacket.
3. If the inlet to the evaporator is a mixture of the outlet vapor from crystallizer and steam outlet from the jacket.

The followings assumptions are proposed:

- Steady state, steady flow operation.
- Potential and kinetic energy effects are negligible
- No chemical reaction.
- Adiabatic compression efficiency is 0.7.

The price of electricity and low pressure steam for heating (LPS) are estimated to be 0.05 ($/kW h) and 3.17x10^{-6} ($/kJ) respectively, and the cost of the heating agent used in the heater 0.33 $/kJ [9].

The used basis for calculation is listed in Table 3 for Q_L. There three value can be calculate, based on what is the inlet to the evaporator of heat pump:

1. If the inlet to the evaporator is steam V at T_4=25^oC and out at T_5=12^oC;
2. If the inlet to the evaporator is steam S at T_4=25^oC and out at T_5=12^oC;
3. If the inlet to the evaporator is steam V (V_o & S) at T_4=25^oC and out at T_5=12^oC. (See Figs. 5, 6 and 7).

The used high-efficiency heat pump manufactured has a COP of (2.3-5) in the heating mode [8].

The basis of calculation is presented in Table 3.

The calculations of flow rate of outlet steam from indirect crystallizer V, flow rate of inlet steam fed to the

![Graph showing dependency of saving factor (S_{EE}, E_{ES}) on coefficient of performance (COP).](image)

![Graph showing cost of heating inlet air with: a - Heat pump, b - Electrical heater and c - LPS steam in heater.](image)

![Graph showing dependency of saving factor on different heat pump coefficients of performance.](image)
Table 4A. Material and energy balances in the case of adding heat pump on outlet vapor line from crystallizer.

<table>
<thead>
<tr>
<th>COP</th>
<th>X_f</th>
<th>V_o</th>
<th>S</th>
<th>Q_L</th>
<th>Win</th>
<th>Q_H</th>
<th>Q_s</th>
<th>Q_J</th>
</tr>
</thead>
<tbody>
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<td>0.22</td>
<td>633.333</td>
<td>6596.263</td>
<td>834427.2</td>
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<td>1476294.316</td>
<td>1523737</td>
<td>47442.35</td>
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<tr>
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<td>6596.263</td>
<td>834427.2</td>
<td>556284.8148</td>
<td>1390712.037</td>
<td>1523737</td>
<td>133024.63</td>
</tr>
<tr>
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<td>633.333</td>
<td>6596.263</td>
<td>834427.2</td>
<td>417213.6111</td>
<td>1251640.833</td>
<td>1523737</td>
<td>272095.83</td>
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<tr>
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<td>0.22</td>
<td>633.333</td>
<td>6596.263</td>
<td>834427.2</td>
<td>333770.8889</td>
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<td>355538.56</td>
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<tr>
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<td>6596.263</td>
<td>834427.2</td>
<td>278142.4074</td>
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<td>411167.04</td>
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<tr>
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<td>633.333</td>
<td>6596.263</td>
<td>834427.2</td>
<td>208606.8056</td>
<td>1043034.028</td>
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<td>480702.64</td>
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Table 4B. The Cost and saving factor in the case of adding heat pump on outlet vapor line from crystallizer.

<table>
<thead>
<tr>
<th>COP</th>
<th>$\Phi_s$ ($/hr$)</th>
<th>$\Phi_H$ ($/hr$)</th>
<th>$\Phi_J$ ($/hr$)</th>
<th>$\Phi_T$ ($/hr$)</th>
<th>$S_E$ ($/hr$)</th>
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</thead>
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<tr>
<td>2.3</td>
<td>5.160245</td>
<td>6.240374525</td>
<td>0.480392251</td>
<td>6.720767</td>
<td>-30.2412</td>
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<td>5.408324588</td>
<td>0.751688076</td>
<td>6.160013</td>
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<tr>
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<td>2.028121721</td>
<td>1.853827365</td>
<td>3.881949</td>
<td>24.772</td>
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</table>

jacket S, Heat accepted by evaporator $Q_L$, work input of heat pump $W_H$, heat generated by condenser $Q_H$, heat generated by heater without heat pump $Q_s$, and the amount of the heat that needed after preheating form heat pump $Q_J$ are presented in Table 4A. All calculations are at constant feed concentration and the feed to heat pump evaporator consists of S and $V_o$.

Table 4B shows the calculations of total operating cost without heat pump $\Phi_s$; the total operating cost of heat pump $\Phi_H$; the operating cost of the heat heating make up (after preheating by heat pump) $\Phi_J$; the total operating cost of the process with a heat pump and heater $\Phi_T$; and saving factor $S_E$. All calculations are at constant feed concentration and the feed to heat pump.

Fig. 14. Variation of saving factor with different feed concentrations at constant COP.
The heat saving in an evaporative crystallization processes in the two types (direct and indirect evaporative crystallizers) is studied:

In case of a direct evaporative crystallizer, a noticeable saving factor ranges between 69 to 86 % and 81 to 93 % based on electrical, steam heating, respectively, was achieved by adding a heat pump with variable COP. The process of direct contact evaporative crystallization has an advantage of producing an additional amount of distilled water as a byproduct of the crystallization.

In the case of indirect evaporative crystallizer, noticeable saving factor ranges between 8 to 26 % based on steam heating were achieved by adding a heat pump on the outlet vapor line with variable COP. The process of direct contact evaporative crystallization has an advantage of producing an additional amount of desalinated water, when the main purposes of separation is extraction of minerals, comparing to traditional open solar pond evaporative systems.

REFERENCES