JJMIE
Jordan Journal of Mechanical and Industrial Engineering

Volume 4, Number 3, June 2010
ISSN 1995-6665
Pages 358 - 363

Theoretical Analyses of Energy Saving in Indirect Contact Evaporative Crystallization by Using Combined Cycle of Vapor Recompression Heat Pump and Throttling Valve

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Abstract

The installation of heat pumps in different chemical processes is considered as an important and prospective approach for energy saving. Various crystallization processes such as counter current crystallization, direct and indirect contact crystallization, evaporative crystallization and fractional crystallization from melts are used to be a promising chemical processes where heat pumps can be introduced for the purpose of energy saving. 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. This work presents a theoretical analysis of the technical feasibility and the potential of heat pumps to be used in the process of indirect contact evaporative crystallization. Principle schemes of the process with heat pump and in combination with throttling valve are proposed and the corresponding calculations are performed. The Effect of temperature and initial feed concentration on the energy saving factor are investigated. The average value of this factor was estimated to be 49.6 % when a cooled feed solution enters (T =25 ^oC) to the crystallizer. This factor was found to be increased to 70.4 % when the feed solution inters at its boiling point (T=125 ^oC).The installation of throttling valve at the outlet of the condensate produces (based on feed conditions) an additional amount of vapor and as a result the saving factor increases from 17 % to 22 % .

Keywords: heat pumps; energy saving; crystallization

Nomenclature

F	Feed solution (kg/s)
K	Crystal phase(kg/s)
M	Mother liquor(kg/s)
D	Suspension phase(kg/s)
V_o	Produced vapor(kg/s)
X_F	Salt concentration in feed solution (%)
X_K	Salt concentration in crystal phase (%)
X_M	Salt concentration in mother liquor (%)
X_D	Salt concentration in suspension phase (%)
Xv_o	Salt concentration in vapor phase (%)
φ_{Vo}	Yield of vapor phase (%)
φ_D	Yield of suspension phase (%)
h_F,h_{Vo},h_D,h_K,h_M	Specific enthalpy of feed, primary vapor , suspension, crystal & mother liquor phases (kJ/kg)
h_{Kf}	Specific latent heat of crystallization. (kJ/kg)
Q_C	Heat required for heating the feed solution (kJ/s)
Q_s	heat introduced to the system by heating steam (kJ/s)
T_F	Feed temperature (^oC)
T_b	Solution boiling point temperature(^oC)
S	Input heating steam of crystallizer (kJ/s)
C_F	Heat capacity of feed solution (kJ/kg ^oC)
S_o	Fresh make up steam (kJ/s)
H_{Vo}	Specific latent heat of vaporization(kJ/kg)
H_{in}	Specific enthalpy of heating steam at the inlet of crystallizer (kJ/kg)
H_{out}	Specific enthalpy of heating steam at the outlet of crystallizer (kJ/kg)
P_a	Actual power required for heat pump (kJ/s)
h_o, h_i	Specific enthalpy of vapor, at the inlet and out let of heat pump compressor (kJ/s)
η	Overall efficiency coefficient (%)
α	Ratio of salts concentrations in both feed & suspension phase (%)
V_{th}	Vapor produced as a result of throttling process (kJ/s)
L	Water produced as a result of throttling process (kJ/s)
h_L	Enthalpy of water produced as a result of throttling process
E_e	Cost for recompression ($/h)
E_s	Cost of ordinary process ($/h)
E_{So}	Cost of heating steam (so) ($/h)
Saving factor	(%)

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1. Introduction

Chemical processes are generally characterized as high energy consuming processes; therefore, the operating cost becomes a huge burden on different industries, particularly with the recent soaring prices of oil. Therefore the reduction of energy consumption in these processes is considered a very important factor in determining the economical feasibility of the whole process.

A significant saving in energy consumption can be achieved using heat pumps for various processes in chemical industry [1,2]. The concept of heat pumps depends on increasing the potential (temperature) of operating fluid to the value that would fit to be used in the given chemical process. In vapor recompression heat pump the consumption of electrical energy goes to convert the low potential vapor phase by means of pressurizing into vapor with high potential [3,4]. This operation requires approximately energy in one order less than that for production of the same high potential vapor from its initial liquid phase.

Heat pumps can be potentially used to reduce energy consumption in evaporation, distillation, rectification, and in various methods of crystallization. This can be achieved by using different means of pressurizing low potential operating fluids. Introduction of different types of heat pumps to such as processes reduces the energy consumption considerably. Verk et al [5] and Bsharat [6] reported that saving on energy consumption up to 47 % was obtained when Vapor recompression heat pump was introduced to distillation and water desalination processes. Saving of 34 % to 45 % was also achieved by introducing mechanical heat pump to counter current crystallization process [7]. Energy saving was also achieved by using heat pumps in direct contact evaporative crystallization [8,9].

The aim of the this work is to study the possibility of reducing energy demand for the process of continuous indirect contact evaporative crystallization by using a combined vapor recompression heat pump cycle and throttling valve.

2. Theoretical Background

A schematic diagram, as shown in Figure1 presents a flow diagram of indirect contact evaporative crystallization process using saturated steam as a heating agent. This process is used on a large scale in crystallization and separation of mineral salts from their aqueous solutions such as KCl , K_2CO_3, NaCl and $NaNO_3$, [10,11].The process is carried out in a single-effect crystallizer. Steam, with a flow rate of (S), heats the solution through a contact surface. The enthalpy of the steam is then changed from H_{in} at the inlet to H_{out} at the outlet. vapor amount (V_o) is then produced and directed to a condenser where it condensed and pure water is obtained. A suspension (D) consisting of a crystal phase (K) and mother liquor (M) are formed and separated in a separator at the end of the process.

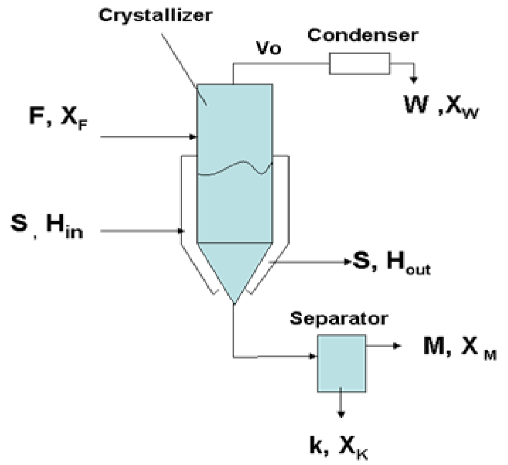

Figure 1: Principle scheme for indirect evaporative crystallization.

The overall material balance around crystallizer can be expressed as:

$$F = D + V_o \tag{1}$$

and

$$D = K + M \tag{2}$$

Balance on solute can be represented as:

$$FX_F = DX_D + V_o X_{Vo} \tag{3}$$

By substituting Eq . (2), in Eq.(3), Eq. (1) can be rewritten as:

$$FX_F = KX_K + MX_M + V_o X_{Vo} \tag{4}$$

Where $X_F, X_D, X_K, X_M, X_{Vo}$ are the salts concentrations in the feed solution (F), suspension (D), crystal (K), Mother liquor (M) and condensate (V_o) phases respectively.

Taking into account that the evaporated water contains zero amount of solute ($X_{Vo} = 0$) Then Eq. (4) became:

$$FX_F = KX_K + MX_M \tag{5}$$

The yield of vapor phase (condensate) and suspension phase can be calculated by solving Eq (1) and Eq. (2) simultaneously as follows:

$$\varphi_{Vo} = \frac{V}{F} = \frac{X_F - X_D}{X_{V_o} - X_D} \tag{6}$$

$$\varphi_D = \frac{D}{F} = 1 - \varphi_{Vo} = \frac{X_{Vo} - X_F}{X_{V_o} - X_D} \tag{7}$$

or

$$X_D = \frac{X_F - X_{Vo}\varphi_{Vo}}{1 - \varphi_{Vo}} \tag{8}$$

If the volatility of solute is assumed to be zero or $X_{Vo} = 0$, then Eq. (6, 7 and 8) became as follows:

$$\varphi_{Vo} = \frac{X_F}{1 - X_D} \tag{9}$$

$$X_D = \frac{X_F}{1 - \varphi_{Vo}} \tag{10}$$

$$\varphi_D = \frac{X_F}{X_D} \tag{11}$$

The energy balance around crystallizer is calculated by**:**

$$Fh_F + Q_s = Vo.h_{Vo} + Dh_D + Kh_{K\,f} \tag{12}$$

Where, h_F, h_{Vo}, h_D are the enthalpies of feed solution, primary vapor, and the suspension respectively. $h_{K\,f}$ is the latent heat of crystallization and Q_s is the introduced heat to the system by heating steam. The heat content of the suspension can be represented as:

$$Dh_D = Kh_K + Mh_M \tag{13}$$

The heat required for heating feed solution Q_C from its feed temperature T_F to its boiling point temperature inside the crystallizer T_b is estimated by the following equation:

$$Q_C = C_F F (T_b - T_F) \tag{14}$$

Where C_F is the heat capacity of the feed solution. The amount of heating steam for Heating and evaporating stages is calculated by:

$$S = \frac{V_o H_{Vo} + Q_C}{H_{in} - H_{out}} \tag{15}$$

Where H_{Vo} is the latent heat of vaporization.

3. Application and Calculations

3.1. Indirect evaporative crystallization with vapor recompression heat pump:

In order to minimize the amount of the energy required to carry out the above mentioned crystallization process, a heat pump is proposed to be used as shown in Figure 2. The stream of the primarily formed vapor is directed to a heating chamber after enhancing its potential by increasing its pressure from P_1 to P_2 by using vapor recompression heat pump.

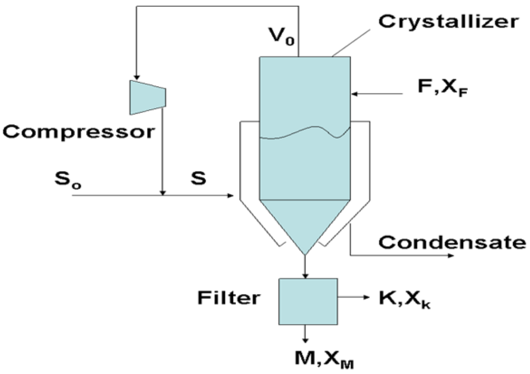

Figure 2: Principle scheme for indirect evaporative crystallization with heat pump.

Thus the required hot fresh steam will be decreased. The amount of this steam can be estimated as:

$$S_o = S - V_o \tag{16}$$

Taking into account Eq (1) & Eq (3) and Solving for V_o:

$$V_o = F(1 - \alpha) \tag{17}$$

Where,

$$\alpha = \frac{X_F}{X_D} \tag{18}$$

The actual power P_a (kW) required for heat pump:

$$P_a = \frac{Vo(h_1 - h_o)}{1000\eta} \tag{19}$$

Where and are the enthalpies of vapor, before and after recompression respectively is the overall efficiency coefficient of the compressor.

In order to examine the efficiency of using a heat pump in the indirect evaporative crystallization, a sample of calculation was carried out for a single effect crystallizer with continuous concentration of K2CO3 solution. The rate of the initial solution was 1000 kg/hr, concentration 10 % (mass), and the final concentration was 60 % (mass). The temperature of the heating steam was 150 ^oC, the pressure inside the crystallizer 1 atm and the final boiling temperature of the solution in the crystallizer was 125 ^oC. Calculations were performed for the following three variants:

- The solution is fed to crystallization process at an initial temperature of 25 ^oC.
- The solution is fed to crystallization process at its boiling point.
- The solution is fed to crystallization process superheated to 135 ^oC

The process of crystallization, was assumed to be ideal, therefore the crystal phase forms according to the theoretical phase diagram of the feed solution.

3.2. Indirect evaporative crystallization with a combined cycle of Vapor recompression and throttling valve:

A modified scheme of the process is shown in Figure 3, where a throttling valve is introduced at the outlet of condensate in order to obtain additional vapor V_{th} by directing the condensate through this valve. As a result, part of this condensate will be changed into vapor. Then, this vapor is mixed with the primary vapor and directed after recompression to the heating chamber.

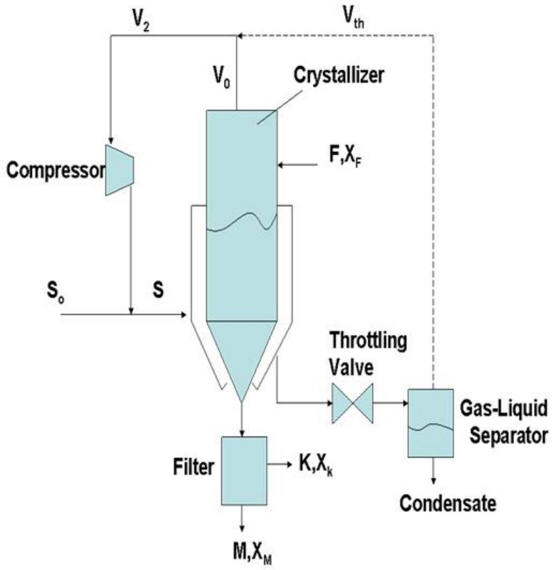

Figure 3: Principle scheme for indirect evaporative crystallization with heat pump and throttling valve.

The amount of V_{th} can be estimated by calculating the energy balance around a throttling valve as follows:

$$SH_{out} = V_{th}h_{th} + Lh_L \tag{20}$$

$$L = S - V_{th} \tag{21}$$

Solving for V_{th}:

$$V_{th} = S\frac{(H_{out} - h_L)}{(h_{th} - h_L)} \tag{22}$$

Where H_{out} is the enthalpy of condensate at the outlet of crystallizer, h_L and h_{th} , are the enthalpies of liquid condensate and vapor after passing through a throttling valve respectively. In this case and as a result of the additional amount of stream of vapor V_{th} produced by a throttling valve, the required amount of make up of fresh steam will be reduced to the amount of:

$$S_o = S - V_o - V_{th} \tag{23}$$

4. Results and Discussions

To evaluate the efficiency of using a heat pump and a throttling valve in the proposed processes, the consumption of energy for the ordinary crystallization process (without heat pump) was calculated and compared to that with a heat pump. Calculation was performed based on the average cost of electrical energy (0.05 $/k.W.h) and low pressure steam (3.17x 10-6 $/kJ) Europe prices [12].

The consumption of electrical energy E_e was estimated according to the operating conditions of vapor recompression process as shown in Fig. 4. The saving factor is defined according to [7] as:

$$Saving\ factor = \left(1 - \frac{Cost\ of\ energy\,consumption\ with\ heat\ pump}{Cost\ of\ energy\,consumption\ without\ heat\ pump}\right) \times 100\% \tag{24}$$

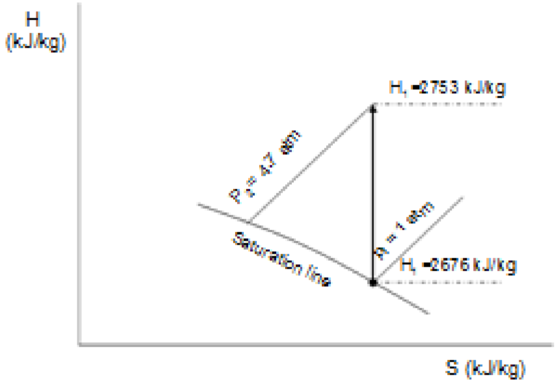

Figure 4: S-H diagram for vapor recompression process.

This factor depends on some of the process variables such as: feed temperature and concentration. The value of this factor was found to be 49.6 %, 70.4 % and 69.7 % for the variants when the feed inters at 25 °C, 125 °C (boiling point) and 135 °C (superheated), respectively.

The maximum saving factor was achieved when the feed enters at its boiling point as illustrated in Figure 5. This can be explained due to the fact that, additional amount of heating steam is needed when the feed solution is cooled. However, when the feed was superheated, an extra amount of vapor was produced.

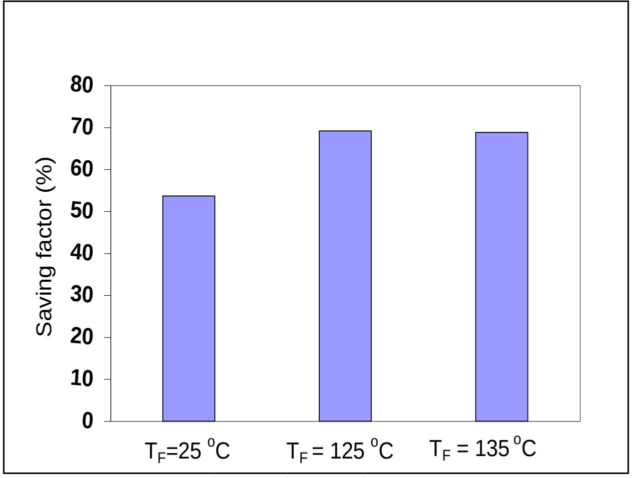

Figure 5: Dependency of saving factor at feed temperature (T_F).

The effect of initial feed concentration on saving factor and on other process variables was also studied. Table.1 show a selected results of calculation for a process when feed concentration was varied from 10 to 60 (wt %), at fixed feed temperature of 25 °C. The obtained data show a slightly decrease in saving factor when the initial feed concentration increases from 10 to 50 %, followed by a sharp decrease and reaches its zero value when the feed concentration reaches 60 % (Figure 6).This decrease is expected and can be explained based on the fact that the increase of feed concentration leads to a decrease in the production of primary vapor V_o which is directed to the heat pump. The value of this vapor goes to zero when the feed inters at concentration closed to saturation point 60 % (Figure 7).

Table 1: Selected results of calculations for K_2CO_3 solution (K_2CO_3 solution, F = 1000 kg/h , TF = 25 °C , Tb =125 °C).

X_F (%)	10 %	20 %	30 %	40 %	50 %	60 %
V_o (kg/h)	833.3	666.7	500.0	333.3	166.6	0
S_o (kg/h)	426.7	364.7	298.9	233.2	167.5	101.6
S (kg/h)	1260.0	1031.4	798,9	566.5	334.1	101.6
E_{so} ($/h)	3.05	2.60	2.14	1.66	1.19	0.72
E_e ($/h)	1.13	0.87	0.615	0.36	0.15	0
E_s ($/h)	9.01	7.37	5.71	4.05	2.38	0.72
Saving ($/h)	4.83	3,89	2.96	2.01	1.03	0
Saving factor (%)	53.6	52.8	51.8	49.8	43.5	0

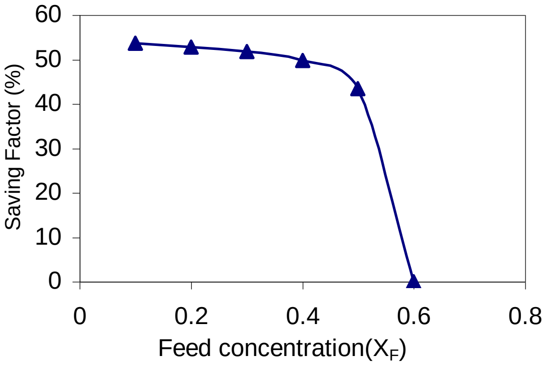

Figure 6: Dependency of saving factor on feed concentration (X_F).

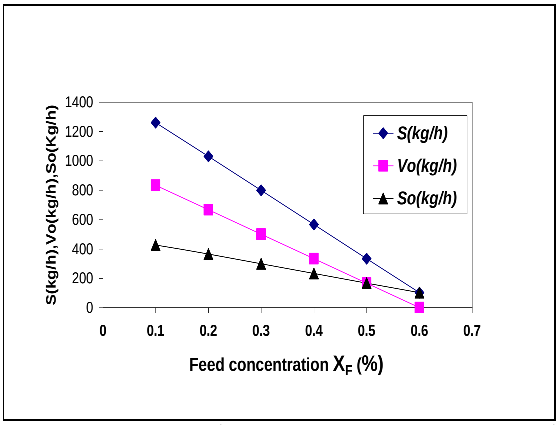

Figure 7: Dependency of primary vapor (V_o), required steam for ordinary process (S) and for a process with heat pump (S_o) on feed concentration (X_F).

Furthermore data illustrated in Figure 7 show that the total required steam for the process with heat pump (S_o) comparing to that without heat pump (S), was reduced by the value equal to the amount of the produced primary vapor. Calculations show that when a throttling valve was installed in combination with a heat pump, an additional saving of 17-22 % (based on initial feed concentration) was achieved.

5. Conclusions

Installation of vapor recompression heat pump in indirect evaporative crystallization process can save energy. The principle schemes and analysis of such process are illustrated in this study. The effect of feed temperature and concentration are analyzed and the energy saving factor was determined. This factor, was found to be in the range of 43 to 71 % based on the entrance feed conditions (temperature & concentration).The combination between vapor recompression heat pump and throttling valve (installed at the outlet of condensate), was found to be produced (based on feed conditions) an additional saving of 17 to 22 %.

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