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Optimum Surface Area Distribution of Multiple-effect Evaporator for Minimizing Steam Use in Raw Sugar Manufacturing

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The sugar juice evaporation process consists of juice heater, multiple-effect evaporator, and crystallizer. The juice heater increases juice temperature from the ambient temperature to the boiling point before entering the multiple-effect evaporator. Water evaporation in the evaporator takes place in many stages at decreasing pressures. The output of the evaporator is concentrated sugar juice or syrup. The evaporation of the remaining water content in syrup occurs in the crystallizer. Both juice heating in the juice heater and water evaporation in the crystallizer require high-temperature vapor, which is bled from the evaporator. Therefore, the model of the juice evaporation process consists of sub-models of the three components and interaction between them through mass and energy balances. The energy efficiency of the process can be measured from the steam input required to operate the process relative to the production of raw sugar by the process. The proposed model shows that the steam requirement depends on distributions of fixed evaporator and juice heater surfaces. The model is used to find the optimum evaporator and juice heater surface area distributions that minimize the required steam input for a specified value of processed juice flow rate.

1. Introduction

Multiple-effect evaporator is one of the three components of the juice evaporation process in raw sugar manufacturing. The other two components are juice heater and crystallizer. The juice heater is used to raise the temperature of incoming juice to the boiling point before the juice is sent to the evaporator. The crystallizer is used to evaporate the remaining water content of concentrated juice leaving the evaporator. The output of the crystallizer is raw sugar. The evaporation process requires a supply of low-pressure steam from a turbine.

Pinch analysis has identified the multiple-effect evaporator as the most intensive thermal energy consumer in raw sugar manufacturing process (Cortes et al., 2010). Therefore, previous suggestions to improve the process performance have mostly focused on the multiple-effect evaporator. Urbaniec et al. (2000) used Process Integration methodology to demonstrate that retrofitting sugar evaporation process led to energy saving. Heluane et al. (2007) investigated the problem of optimizing sugar evaporation process through operation scheduling of the evaporator. Ensinas et al. (2007) used a thermo-economic procedure to optimize the design of multiple-effect evaporator. Higa et al. (2009) showed that increasing the number of evaporator effects and using vapor bleeding for juice heating led to reduced steam consumption. Sharan and Bandyopadhyay (2015) proposed an analytical method for integrating the multiple-effect evaporator with background process to minimize steam consumption. Energy efficiency can also be increased by optimizing the distribution of heating surface area among the effects of the evaporator. Criteria for optimum surface area distribution proposed by previous investigations are based on simplifying assumptions. Hugot (1986) assumed that boiling temperature rise of sugar juice was proportional to the temperature drop of the juice. Jayes (2004) assumed that the latent heat of evaporation of saturated liquid water did not vary with pressure. Recently, Chantasiriwan (2015) proposed a more realistic model of multiple-effect evaporator for determining the optimum surface area distribution among vessels of the evaporator affected by fouling. However, vapor bleeding is ignored under the assumption that vapor supplied to the juice heater and the crystallizer comes from another source. A more

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realistic model should take into account vapor bleeding from the evaporator as normally carried out by sugar factories. In this paper, a model of sugar juice evaporation process is presented. This model takes into account interactions between the three components of the process through mass and energy balances. It is then used to find the optimum distribution of a given total heating surface area among the effects of the evaporator that maximizes the steam economy, which is defined as the ratio of water content of the incoming sugar juice to the amount of steam required to run the process, subjected to a set of specified constraints.

2. Evaporation process

Figure 1 shows the schematic representation of the sugar juice evaporation process. Solid line represents steam and vapor, dashed line represents sugar juice, and dotted line represents condensate. The multiple-effect evaporator requires a supply of saturated steam at pressure p_0. The thermal energy released by the condensation of the steam results in the evaporation of water in sugar juice at a lower pressure p_1 in the first effect (E1). Vapor leaving all effects except the last effect (E4) is used to evaporate water in sugar juice in the succeeding effect. Condensate from E1 is used as feed water for the boiler. Flash tanks are placed after E2 and E3. F1 receives condensate at pressure p_1 from E2 and H1, and produces vapor and condensate at pressure p_2. The vapor is used for evaporation of sugar juice in E3. Similarly, F2 receives condensate from three sources. Vapor produced by F2 is sent to E4. The condensate leaving F2 is collected in a storage tank.

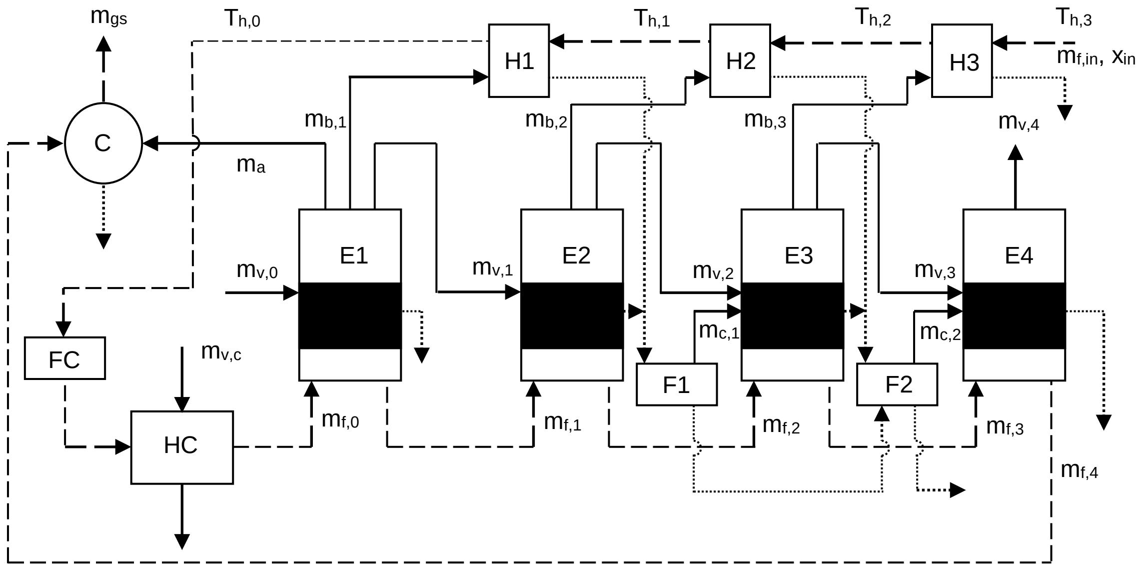

Figure 1: Sugar juice evaporation system.

The juice heater consists of four tubular heat exchangers (HC, H1, H2, and H3). Incoming diluted juice at the flow rate of $m_{f,in}$ and the temperature of $T_{h,3}$ passes successively through H3, H2, and H1, resulting in the temperature increase from $T_{h,3}$ to $T_{h,0}$. Vapor used to increase juice temperature in H1, H2, and H3 is bled, respectively, from the 1st, 2nd, and 3rd effects of the evaporator. The juice leaving H1 is at a pressure slightly larger than the atmospheric pressure so that dissolved gases in the juice are removed in FC. Before entering the first effect of the evaporator, the juice pressure is raised from the atmospheric pressure to p_1, and the juice temperature is increased to the boiling point in HC, which uses low-pressure steam as the heating medium.
The crystallizer (C) also requires bled vapor from the 1st effect of the evaporator. Energy released by vapor condensation is used to evaporate the water content of the concentrated juice from the 4th effect. Outputs from C are raw sugar and condensate.

3. Mathematical model

The mathematical model of the evaporation process consists of sub-models of evaporator, juice heater, and crystallizer. Equations of these models are mass balance equations, energy balance equations, and equations of thermo-physical properties. The energy balance equations of the evaporator are

$$\left(1-\varepsilon_e\right)m_{v,0}h_{vl,0}+m_{f,0}\left(h_{f,1}^{(in)}-h_{f,1}^{(out)}\right)=\left(m_a+m_{v,1}+m_{b,1}\right)\left(h_{v,1}-h_{f,1}^{(out)}\right) \quad (1)$$

$$\left(1-\varepsilon_e\right)m_{v,1}h_{vl,1}+\left(m_{f,0}-m_a-m_{v,1}-m_{b,1}\right)\left(h_{f,2}^{(in)}-h_{f,2}^{(out)}\right)=\left(m_{v,2}+m_{b,2}\right)\left(h_{v,2}-h_{f,2}^{(out)}\right) \quad (2)$$

$$\left(1-\varepsilon_e\right)\left(m_{v,2}+m_{c,1}\right)h_{vl,2}+\left(m_{f,0}-m_a-m_{v,1}-m_{b,1}-m_{v,2}-m_{b,2}\right)\left(h_{f,3}^{(in)}-h_{f,3}^{(out)}\right)=\left(m_{v,3}+m_{b,3}\right)\left(h_{v,3}-h_{f,3}^{(out)}\right) \quad (3)$$

$$\left(1-\varepsilon_e\right)\left(m_{v,3}+m_{c,2}\right)h_{vl,3}+\left(m_{f,0}-m_a-m_{v,1}-m_{b,1}-m_{v,2}-m_{b,2}-m_{v,3}-m_{b,3}\right)\left(h_{f,4}^{(in)}-h_{f,4}^{(out)}\right)=m_{v,4}\left(h_{v,4}-h_{f,4}^{(out)}\right) \quad (4)$$

where $h_{vl,i}$ is the latent heat of evaporation at saturation temperature T_i, $h_{v,i}$ is the saturated steam enthalpy at T_i, and $h_{f,i}$ is the sugar juice enthalpy in effect i, which is the product of specific of heat capacity of sugar juice (c_{pf}) and juice temperature (T_f). Equations for h_{vl}, h_v, and c_{pf} are provided by Rein (2007). It is assumed that the heat-loss fraction ε_e in evaporator is 0.005 in the 1st and 2nd effects, and 0.015 in the 3rd and 4th effects. Mass and energy balances of the flash tanks yield the following expressions for vapor mass flow rates ($m_{c,1}$ and $m_{c,2}$) from flash tanks F1 and F2.

$$m_{c,i}=\left[m_{v,i}+m_{b,i}+\sum_{j=1}^{i-1}\left(m_{v,j}+m_{b,j}\right)f\left(T_j,T_{j+1}\right)\right]f\left(T_i,T_{i+1}\right) \quad (5)$$

where

$$f\left(T_{i-1},T_i\right)=\frac{h_v\left(T_{i-1}\right)-h_v\left(T_i\right)-h_{vl}\left(T_{i-1}\right)+h_{vl}\left(T_i\right)}{h_{vl}\left(T_i\right)} \quad (6)$$

Juice temperature (T_f) is assumed to be the saturation temperature. It is larger than the boiling point of saturated liquid water at the same pressure due to the concentration of dissolved solids in juice (Honig, 1963). It should be noted that boiling temperature rise due to hydrostatic pressure head is not taken into account in this model because the evaporator is assumed to be of a design in which the effect of hydrostatic pressure head on boiling temperature is negligible.

The juice concentration (x_i) leaving effect i of the evaporator is determined from the mass balance of dissolved solids.

$$x_i=\frac{m_{f,in}x_{in}}{m_{f,0}-m_a\left(1-\delta_{i0}\right)-\sum_{j=1}^{i}\left(m_{v,j}+m_{b,j}\right)} \quad (7)$$

where δ_{i0} is the Kronecker delta. Note that since there is no vapor bled from the 4th effect, $m_{b,4}=0$.

Additional equations are obtained from the requirement that the rate of heat transfer across evaporator surface (A_i) in effect i is equal to the rate of heat transfer released by condensing steam in that effect.

$$U_iA_i\left[T_{i-1}-0.5\left(T_{f,i}^{(in)}+T_{f,i}^{(out)}\right)\right]=\left(1-\varepsilon_e\right)\left(m_{v,i-1}+m_{c,i-1}\right)h_{vl,i-1} \quad (8)$$

The evaporator is assumed to be of the falling-film type, for which the correlation of heat transfer coefficient is provided by Pacheco and Frioni (2004).

$$U_i=6.9796e^{-0.019082\left(x_{i-1}+x_i\right)} \quad (9)$$

For the juice heater, the requirement that the latent heat of condensation of the bled vapor equals the juice enthalpy increase in H1, H2, and H3 yields

$$\left(1-\varepsilon_h\right)m_{b,i}h_{vl,i}=m_{f,in}c_{p,i}\left(T_{h,i-1}-T_{h,i}\right) \quad (10)$$

where $c_{p,i}$ is the average heat capacity of the juice, and the heat-loss fraction ε_h in juice heater is 0.05. In addition, the requirement that the heat transfer across the surfaces of H1, H2, and H3 equals the increase in enthalpy of the juice yields

$$T_{h,i-1}=T_i-\left(T_i-T_{h,i}\right)e^{-U_{h,i}A_{h,i}/m_{f,in}c_{p,i}} \quad (11)$$

If juice velocity is 2.0 m/s, the overall heat transfer coefficient of the juice heater is (Hugot, 1986).

$$U_{h,i} = 0.0076 T_i \quad (12)$$

After leaving H1, the juice pressure (p_{in}) is a little above the atmospheric pressure (p_{out}). The juice is allowed to flash in FC, resulting in a reduced mass flow rate ($m_{f,0}$) that is determined from

$$m_{f,0} = m_{f,in}\left[1 - f\left(T_{in}, T_{out}\right)\right] \quad (13)$$

The juice pressure is increased to p_1 before entering the first effect. Furthermore, it is heated in HC by the exhaust steam. The following equations for HC are similar to corresponding equations for H1, H2, and H3.

$$\left(1 - \varepsilon_h\right) m_{v,c} h_{vl,c} = m_{f,0} c_{p,c} \left(T_1 - T_{out}\right) \quad (14)$$

$$T_1 = T_c - \left(T_c - T_{out}\right) e^{-U_{h,c} A_{h,c} / m_{f,0} c_{p,c}} \quad (15)$$

$U_{h,c}$ is approximately 1.0 kW/m^2.K (Peacock and Love, 2003). The steam pressure in HC (p_c) is assumed to be controlled in such a way that the juice temperature is exactly T_1 at the exit of HC. The surface area of HC ($A_{h,c}$) is 800 m^2, which is large enough that p_c does not exceed p_0.
The crystallizer may be modelled as a single-effect evaporator. It uses the vapor bled from the first effect to evaporate the remaining water content in the syrup leaving the evaporator. Ideally, the amount of water to be evaporated is the water content of the syrup. In practice, however, more water is required, and a correction factor (C) must be included. Previous works indicate that C is in the range of 2.0 to 2.2 (Reid and Rein, 1983; Rein, 2007). In this paper, the ratio of 2.1 is assumed. Therefore,

$$m_a = \frac{2.1\left[m_{f,0} - m_a - \sum_{j=1}^{4}\left(m_{v,j} + m_{b,j}\right) - 0.01 m_{f,0} x_0\right] h_{vl,4}}{h_{vl,1}} \quad (16)$$

4. Determination of performance parameters

It should be noted that, because the juice temperature at the exit of HC is assumed to be T_1, HC is uncoupled from the rest of the system as far as the solution to the system is concerned. For the rest of the system, there are 28 variables (x_{in}, $m_{f,in}$, $m_{f,0}$, $m_{v,0}$ – $m_{v,4}$, $m_{b,1}$ – $m_{b,3}$, $T_{h,0}$ – $T_{h,3}$, A_1 – A_4, and $A_{h,1}$ – $A_{h,3}$) and 16 equations Eqs(1) – (4), (8), (10), (11), (13), and (16)]. By imposing the value of juice concentrations (x_4) at the outlet of the evaporator, Eq. (7) yields an additional equation. Two more equations are obtained if the total evaporator surface ($A_{tot} = A_1 + A_2 + A_3 + A_4$) and the total juice heater surface ($A_{h,tot} = A_{h,1} + A_{h,2} + A_{h,3}$) are given. Furthermore, it is a common practice in the sugar evaporation process to specify values of x_{in}, x_4, p_0, p_4, $T_{h,0}$, and $T_{h,3}$. As a result, there are 4 free parameters.
For a given set of these parameters, the solution of the system of equations governing the operation of the juice evaporation process can be found. Two performance parameters are obtained from the solution. The first parameter is $m_{f,in}$, and the second parameter is the steam economy (SE), defined as

$$SE = \frac{\left(1 - 0.01 x_{in}\right) m_{f,in}}{m_{v,0} + m_{v,c}} \quad (17)$$

The first parameter is related to revenue earned by the sugar factory, whereas the second parameter is related to energy use by the factory.

5. Results and discussion

In the following simulation results, the juice concentration at inlet of the juice heater (x_{in}) is 12%, the juice concentration at outlet of the evaporator (x_4) is 65%, the steam pressure (p_0) at the inlet of the evaporator is 200 kPa, the vapor pressure (p_4) at the outlet of the evaporator is 16 kPa, the juice temperature ($T_{h,3}$) at the inlet of the juice heater is 30°C, and the juice temperature ($T_{h,0}$) at the outlet of the juice heater is 103°C. The total evaporator surface (A_{tot}) is 12,000 m^2, and the total juice heater surface ($A_{h,tot}$) is 2,500 m^2.
If vapor is bled from only the 1st and 2nd effects of the evaporator, $A_{h,3} = 0$, and there are only 3 free parameters, which are A_1, A_2, and A_3. Figure 2 shows that, for fixed values of A_1 and A_2, increasing p_1 results in decreasing $m_{f,in}$ and increasing SE. In practice, p1 is not allowed to be lower than a specified value because

bled vapor from the 1st is required for the crystallizer, which is designed to operate at a design pressure. It is assumed that p1 is 150 kPa. By specifying the value of p1, there are only 2 free parameters left - A1 and A2.

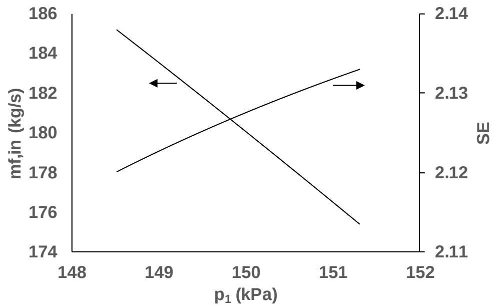

Figure 2: Variations of input juice mass flow rate and steam economy with 1^{st}-effect pressure for the evaporator surface area distribution in which A_1 = 4,800 m^2 and A_2 = 2,500 m^2.

Figure 3 shows that, for a given value of A_1, there exists the optimum value of A_2 that maximizes $m_{f,in}$. The corresponding evaporator surface area distribution is known as the A_2-optimized evaporator surface area distribution.

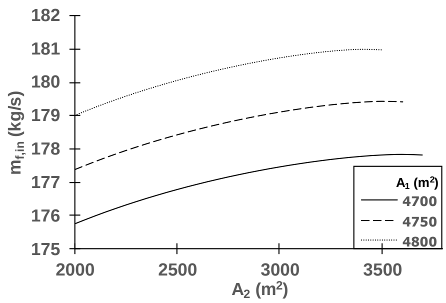

Figure 3: Variations of input juice mass flow rate with 2^{nd}-effect surface and three 1^{st}-effect surfaces for the evaporator surface area distribution that yields the 1^{st} effect pressure of 150 kPa.

Figure 4 shows that, for the A_2-optimized evaporator surface area distribution, $m_{f,in}$ increases with A_1, whereas SE decreases with increasing A_1. It can be seen that it is impossible to maximize both parameters. A typical sugar factory puts the priority on the minimum juice processing capacity of the evaporation process because the entire raw sugar manufacturing process will be affected if the mass flow rate of processed juice is too low. Therefore, it is practical to impose a specified value of $m_{f,in}$ as another constraint of the system.

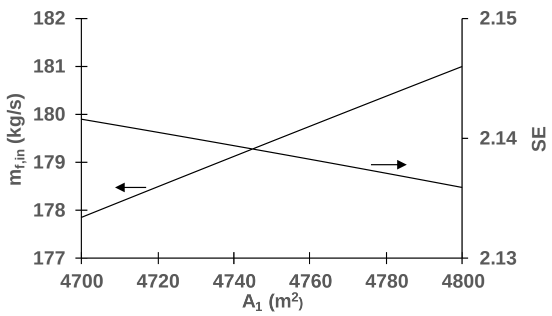

Figure 4: Variations of input juice mass flow rate and steam economy with 1^{st}-effect surface for the A_2-optimized evaporator surface area distribution.

By imposing the requirement that $m_{f,in}$ = 180 kg/s, there are unique evaporator and juice heater surface area distributions for a given value of $A_{h,3}$. If $A_{h,3}$ = 0 m^2, it is found that A_1 = 4,768.1 m^2, A_2 = 3,487.1 m^2, A_3 =

1,232.7 m^2, A_4 = 2,512.1 m^2, $A_{h,1}$ = 782.6 m^2, $A_{h,2}$ = 1,717.4 m^2, and SE = 2.138. Table 1 shows evaporator and juice heater surface area distributions for 4 values of $A_{h,3}$. It can be seen that SE decreases monotonically with increasing $A_{h,3}$. The most energy efficient vapor bleeding scheme uses vapor bled from only the first two effects of the evaporator.

Table 1: Optimum evaporator and juice heater surface area distributions that result in the mass flow rate of input sugar juice of 180 kg/s.

$A_{h,3}$ (m^2)	A_1 (m^2)	A_2 (m^2)	A_3 (m^2)	A_4 (m^2)	$A_{h,1}$ (m^2)	$A_{h,2}$ (m^2)	SE
0	4,768.1	3,487.1	1,232.7	2,512.1	782.6	1,717.4	2.138
100	4,815.3	3,332.2	1,241.9	2,610.6	841.2	1,558.8	2.122
200	4,860.6	3,210.3	1,266.6	2,662.5	901.3	1,398.7	2.107
300	4,905.2	3,114.1	1,299.3	2,681.4	963.5	1,236.5	2.093

6. Conclusions

The proposed model of the evaporation process for raw sugar manufacturing indicates that, if the total evaporator and juice heater surface areas are fixed, juice concentrations are specified at the inlet and outlet of the process, juice temperatures are specified at the inlet and outlet of the juice heater, and steam pressures are specified at the inlet and outlet of the evaporator, the process performance depends on 4 parameters. Process performance is measured by the mass flow rate of processed sugar juice and the ratio of steam required to run the process to the processed sugar juice. If the first-effect pressure is specified, the number of free parameters is reduced to 3. Two parameters are related to the distribution of the fixed evaporator surface area among the effects of the evaporator, and the other parameter is related to the distribution of the fixed juice heater surface area among the heat exchangers of the juice heater. Simulation results indicate that the minimum steam required to process a specified amount of sugar juice is minimum when vapor is bled from only the first two effects and the evaporator surface area is optimally distributed among the 4 effects.

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