Simulation of Quadruple-Effect Evaporator with Vapor Bleeding Used for Juice Heating

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***Abstract*—Quadruple-effect evaporator is used to increase the concentration of sugar juice in a series of four pressure vessels. Vapor bled from the first three vessels is used to increase the juice temperature in juice heater to the saturation temperature at the inlet of the evaporator. This paper presents the model of heating and evaporation of sugar juice in juice heater and evaporator. The model is used to investigate how variations of surfaces in juice heater and evaporator affect the performance of the system.**

***Index Terms*—multiple-effect, multi-effect, evaporation, raw sugar, modeling, steam economy**

I. Introduction

Juice extracted from sugar cane in milling unit of a sugar factory has low concentration due to addition of water to facilitate the milling process. Quadruple-effect evaporator may be used to remove a sufficiently amount water from the sugar juice so that the juice is concentrated enough to be sent to the crystallization unit. Since quadruple-effect requires a supply of a high-pressure steam for its operation, efficient design and operation will result in the optimum use of steam.

Quadruple-effect evaporator is usually designed so that the heating surface is efficiently used if juice entering the evaporator is at saturation temperature. Since the temperature of the extracted juice leaving the milling unit is at the ambient temperature, juice heater is required to raise juice temperature. The heat source for the juice heater is vapor bled from the evaporator. It is, therefore, obvious that a realistic simulation of quadruple-effect evaporator must take into account its interaction with juice heater. Previous studies concerning multiple-effect evaporator have paid little attention to this interaction [1]-[7].

In this paper, a coupled model of the quadruple-effect evaporator and juice heater is presented. This model takes into account interaction between the quadruple-effect evaporator and juice heater through mass and energy balances. It is then used to investigate the effects of additional juice heater surface and evaporator surface on the performance of the system.

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II. Quadruple-Effect Evaporator

Fig. 1 shows the schematic representation of quadruple-effect evaporator. High-pressure steam is supplied to the inlet of the first vessel (E1) of the evaporator. The thermal energy released by the condensation of the steam causes the evaporation of sugar juice at a lower pressure p_1 in the first vessel, resulting in vapor and more concentrated sugar juice. The vapor leaving all vessels (E1, E2, and E3) except the last vessel (E4) is used to evaporate sugar juice in succeeding vessel. In addition, vapor is bled from all vessels of the evaporator except the last one, and is used to increase juice temperature in the juice heater. The arrangement in Fig. 1 makes use of condensate flash recovery in order to improve the efficiency of the evaporator. A flash tank is placed after each effect except the last one. The first flash tank (F1) receives condensate from the first vessel at pressure p_0 to produce vapor and condensate at pressure p_1. Each of the other flash tanks (F2 and F3) receives condensate from the preceding vessel and the preceding flash tank at pressure p_i to produce vapor and condensate at pressure p_{i+1}.

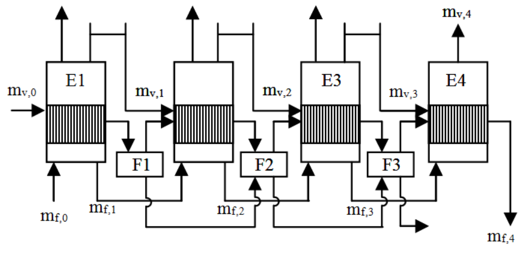

Figure 1. Quadruple-Effect evaporator.

The evaporator model is a modification of the model proposed by Chantasiriwan [7] with inclusion of vapor bleeding. For effect i, the mass balance equation is:

$$m_{f,i} + m_{v,i} = m_{f,i-1} \quad (1)$$

Equation (1) can be immediately solved for $m_{f,i}$.

$$m_{f,i} = m_{f,0} - \sum_{j=1}^{i} m_{v,j} \quad (2)$$

The energy balance equation for effect i is:

$$(1-\varepsilon)\left(m_{v,i-1} + m_{c,i-1}\right)h_{vl,i-1} + \left[m_{f,0} - \sum_{j=1}^{i-1}\left(m_{v,j} + m_{b,j}\right)\right]\left(h_{f,i}^{(in)} - h_{f,i}^{(out)}\right) = \left(m_{v,i} + m_{b,i}\right)h_{vl,i} \quad (3)$$

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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. It is assumed that a fraction ε of heat is lost in each vessel. Rein [8] suggests that ε = 0.015. Note that, since there is no vapor bleeding from effect 4, $m_{b,4} = 0$.

The mass and energy balances in the flash tank are used to find $m_{c,i}$.

$$m_{c,i} = \left(\sum_{j=0}^{i-1} m_{v,j} \right) f\left(T_{i-1}, T_i\right) \tag{4}$$

where:

$$f\left(T_{i-1}, T_i\right) = \frac{h_v\left(T_{i-1}\right) - h_v\left(T_i\right) - h_{vl}\left(T_{i-1}\right) + h_{vl}\left(T_i\right)}{h_{vl}\left(T_{i-1}\right)} \tag{5}$$

In order for the analysis to be possible, equations for h_{vl}, h_v, and h_f (in kJ/kg) are required Equations for latent heat of evaporation of water and enthalpy of saturated steam are obtained from Rein [8].

$$h_{vl}\left(T\right) = 2492.9 - 2.0523T - 3.0752 \times 10^{-3} T^2 \tag{6}$$

$$h_v\left(T\right) = 2502.04 + 1.8125T + 2.585 \times 10^{-4} T^2 - 9.8 \times 10^{-6} T^3 \tag{7}$$

where T is the saturated steam temperature (in °C), and is related to the saturated steam pressure p (in kPa) by:

$$T = -227.03 + \frac{3816.44}{18.3036 - \ln\left(7.5p\right)} \tag{8}$$

Specific enthalpy of juice at inlet and exit of effect i may be written as the product of specific enthalpy of sugar juice and juice temperature ($h_f = c_{pf}T_f$). Both quantities vary from inlet to exit of effect i. T_f is greater than the boiling point of saturated liquid water at the same pressure due to the concentration of dissolved solids in juice. According to a simple correlation by Honig [9]:

$$T_{f,i}^{(in)} = T_i + \frac{2x_{i-1}}{100 - x_{i-1}} \tag{9}$$

$$T_{f,i}^{(in)} = T_i + \frac{2x_{i-1}}{100 - x_{i-1}} \tag{10}$$

Mass balance of dissolved solids yields the equation for juice concentration x_i (in %) as follows.

$$x_i = \frac{m_{f,0} x_0}{m_{f,0} - \sum_{j=1}^{i} m_{v,j}} \tag{11}$$

Finally, the equation for specific heat capacity of sugar juice is obtained from Bubnik *et al.* [10].

$$c_{pf}\left(T_f, x\right) = 4.1868 - 0.0297x + 7.5 \times 10^{-5} x T_f \tag{12}$$

In addition to equations of mass and energy balances, there is heat transfer equation in each effect, which is

$$U_i A_i \left[T_{i-1} - T_{f,i}^{(out)} \right] = \left(1 - \varepsilon\right)\left(m_{v,j-1} + m_{c,j-1}\right) h_{vl,i-1} \tag{13}$$

The correlation for heat transfer coefficient in effects 1-3 is provided by Guo *et al.* [11].

$$U_i = 0.016\left(100 - x_i\right)^{0.4} T_i^{0.25} \tag{14}$$

Rein [8] pointed out that this correlation tends to over-predict the heat transfer coefficient in the last vessel (U_4). Smith and Taylor [12] observed that U_4 correlated with T_4 as follows.

$$U_4 = 0.034T_4 - 1.13 \tag{15}$$

III. Juice Heater

Fig. 2 shows the schematic representation of juice heater. The juice heater is of the indirect type consisting of 4 heat exchangers (HC, H1, H2, and H3). It receives diluted juice at the flow rate of $m_{f,i}$ from the milling unit. After passing through H3, H2, and H1, the juice temperature increases from $T_{h,3}$ to $T_{h,0}$. It is important that $T_{h,0}$ must be above the boiling point at the atmospheric pressure so that dissolved gases in the juice are got rid of by passing the juice through the flash tank (FC). This means that pressure of the diluted juice at the exit of H1 is a little above the atmospheric pressure. Finally, the juice pressure is raised from the atmospheric pressure to the pressure in the first effect of the evaporator (p_1), and the juice is passed through HC to increase its temperature to the boiling point at p_1. High-pressure steam is used to heat the juice.

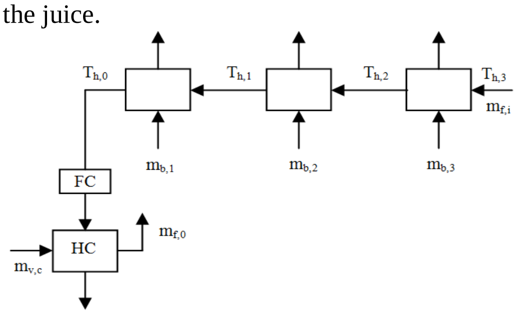


Figure 2. Juice heater.

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

$$m_{b,i} h_{vl,i} = m_{f,i} c_{p,i} \left(T_{h,i-1} - T_{h,i}\right) \tag{16}$$

where $c_{p,i}$ is the average heat capacity of the juice between $T_{h,i}$ and $T_{h,i-1}$.

$$c_{p,i} = \frac{1}{2}\left[c_{pf}\left(T_{h,i}, x_{in}\right) + c_{pf}\left(T_{h,i-1}, x_{in}\right) \right] \tag{17}$$

In addition, the requirement that the heat transfer across the heat exchanger in H1, H2, and H3 equals the increase in enthalpy of the juice yields.

$$T_{h,i-1} = T_i - \left(T_i - T_{h,i}\right) \exp\left(\frac{-U_{h,i} A_{h,i}}{m_{f,i} c_{p,i}} \right) \tag{18}$$

Hugot [13] proposed the following equation for the overall heat transfer coefficient of the juice heater that is used in this investigation.

$$U_{h,i} = 0.007T_i \left(\frac{u}{1.8} \right)^{0.8} \tag{19}$$

If the juice velocity (u) is assumed to be 2.5m/s, the above equation becomes [8]:

$$U_{h,i} = 0.0091T_i \tag{20}$$

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:

$$m_{f,0} = m_{f,i}\left[1 - f\left(T_{in}, T_{out}\right)\right] \tag{21}$$

where T_{in} and T_{out} are saturation temperatures corresponding to p_{in} and p_{out}. Consequently, the juice concentration at the inlet to the first effect (x_0) is related to the juice concentration at the inlet to the juice heater (x_i) as follows.

$$x_0 = \frac{m_{f,i}x_i}{m_{f,0}} \tag{22}$$

The juice pressure is raised to p_1, and juice is heated in HC by the exhaust steam. The model for HC is similar to that for H1, H2, and H3.

$$m_{v,c}h_{vl,c} = m_{f,0}c_{p,c}\left(T_1 - T_{out}\right) \tag{23}$$

$$c_{p,c} = \frac{1}{2}\left[c_{pf}\left(T_{out}, x_0\right) + c_{pf}\left(T_1, x_0\right)\right] \tag{24}$$

$$T_1 = T_c - \left(T_c - T_{out}\right)\exp\left(\frac{-U_{h,c}A_{h,c}}{m_{f,0}c_{p,c}}\right) \tag{25}$$

According to Peacock and Love [14], $U_{h,c}$ is approximately 1.0kW/m^2.K. It may be assumed that the steam pressure in HC (p_c) is controlled so that the juice temperature at the exit of HC is exactly T_1. The heater surface ($A_{h,c}$) is assumed to be large enough so that p_c does not exceed p_0.

IV. Results and Discussion

Since 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. If $A_1 - A_4$ and $A_{h,1} - A_{h,4}$ are specified, Eq. (3), (4), (13), (16), (18), (21), and (22) represent a system of 16 equations with 21 unknowns (x_i, x_0, $m_{f,i}$, $m_{f,0}$, $p_0 - p_4$, $m_{v,0} - m_{v,4}$, $m_{b,1} - m_{b,3}$, and $T_{h,0} - T_{h,3}$). It is assumed that x_i, p_0, p_4, $T_{h,0}$, and $T_{h,3}$ are given so that the number of unknowns is reduced to 16, and the system is determined.

TABLE I. Simulation Results for the Base Case

Effect i	p_i (kPa)	x_i (%)	$m_{v,i}$ (kg/s)	$m_{b,i}$ (kg/s)
0	200.00	15.09	46.10	–
1	136.46	19.90	40.30	5.15
2	90.53	27.94	33.87	7.08
3	57.02	41.83	22.33	11.31
4	20.00	62.80	22.61	–

The juice concentration at inlet of the juice heater is 15%. The pressure of steam supplied to the quadruple-effect evaporator is 200kPa, and the vapor pressure at the outlet of the evaporator is 20kPa. The juice temperature entering H1 is 30°C, and the juice temperature leaving H3 is 103°C. In the base case, the surfaces of E1, E2, E3 and E4 are 3000m^2, and the surfaces of the HC, H1, H2, and H3 are 1000m^2. Simulation results for the base case are shown in Table I.

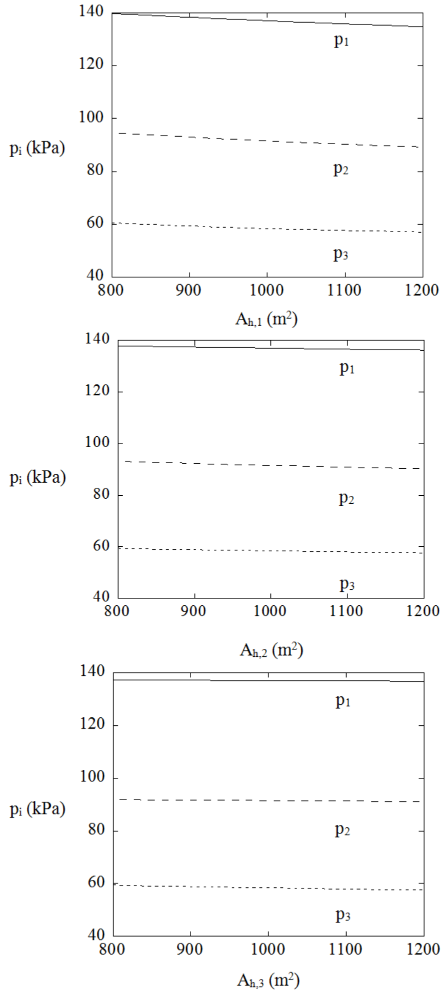
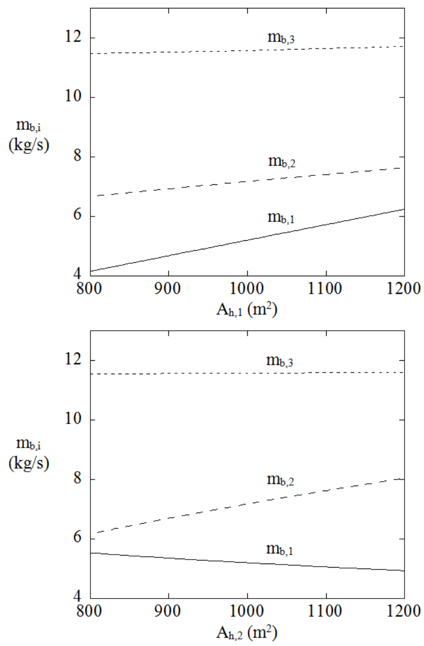


Figure 3. Variations of pressures in effects 1, 2, and 3 of the evaporator with surfaces of H1, H2, and H3.



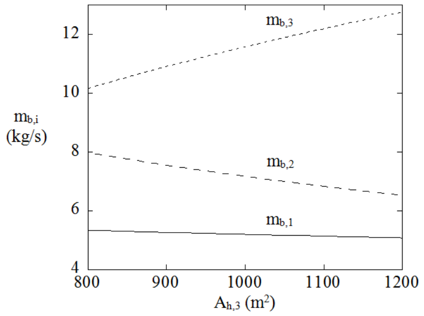


Figure 4. Variations of vapor bled from effects 1, 2, and 3 with surfaces of H1, H2, and H3.

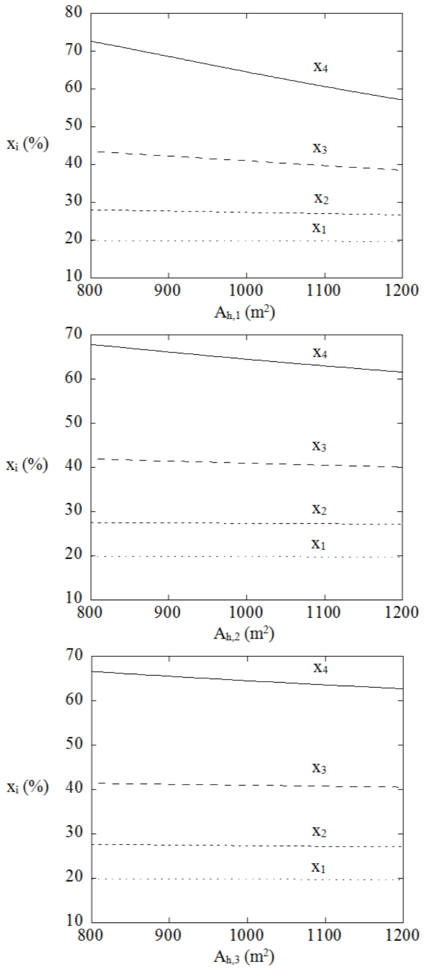


Figure 5. Variations of juice concentrations leaving effects 1, 2, 3, and 4 with surfaces of H1, H2, and H3.

Effects of juice heater surfaces on pressures in the evaporator, mass flow rates of vapor bled from the evaporator, and juice concentrations leaving the evaporator are shown in Fig. 3, Fig. 4, and Fig. 5, respectively. Fig. 3 shows that the effects of $A_{h,1}$ on p_1 and p_2 are slightly more than those of $A_{h,2}$ and $A_{h,3}$. All surfaces, however, have similar effects on p_3. Fig. 4 shows that the effects of $A_{h,1}$, $A_{h,2}$, and $A_{h,3}$ are most pronounced on $m_{b,1}$, $m_{b,2}$, and $m_{b,3}$, respectively. Fig. 5 shows that the effects of juice heater surfaces are most noticeable on x_4. The effect of $A_{h,1}$ on x_4 is greatest, whereas the effect of $A_{h,3}$ is smallest compared with the other surfaces.

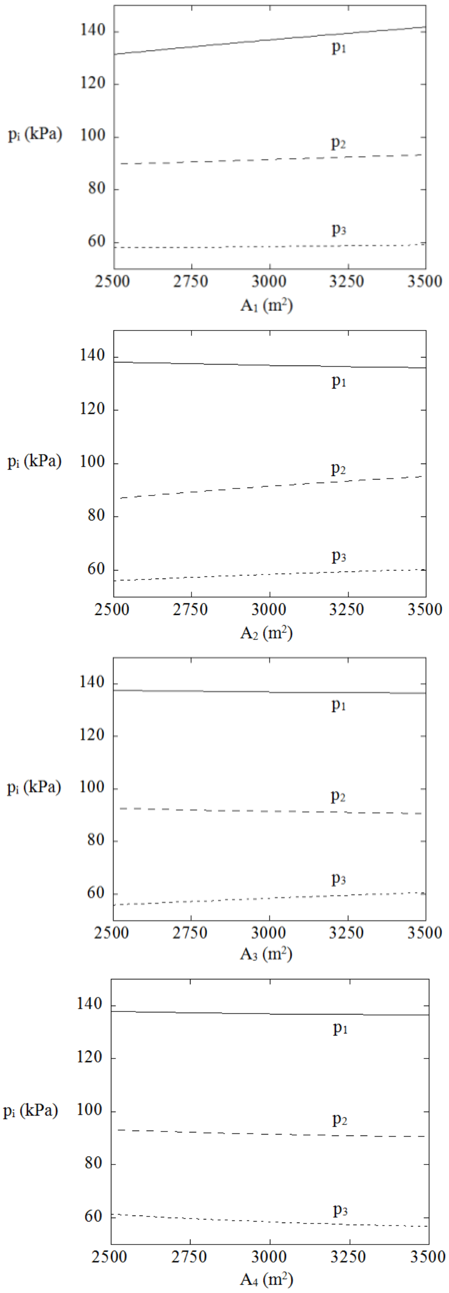


Figure 6. Variations of pressures in effects 1, 2, and 3 with surfaces of E1, E2, E3, and E4.

Effects of evaporator surfaces on pressures in the evaporator, mass flow rates of vapor bled from the evaporator, and juice concentrations leaving the evaporator are shown in Fig. 6, Fig. 7, and Fig. 8, respectively. Fig. 6 shows that the effect of A_1 is most pronounced on p_1. Further-more, the effect of A_2 is most pronounced on p_2, and p_3 is relatively insensitive to all surface variations. Fig. 7 shows that $m_{b,1}$, $m_{b,2}$, and $m_{b,3}$ are relatively more sensitive to A_1 than the other surfaces. Fig. 8 shows that x_4 is relatively more sensitive to the evaporator surfaces than x_1, x_2, and x_3.

Important performance parameters in the operation of the quadruple-effect evaporator are the mass flow rate of sugar juice ($m_{f,i}$) at the inlet of the juice heater and the steam economy, which is defined as the ratio of the amount of water evaporated from diluted juice entering the juice heater as it becomes concentrated juice at the outlet of the evaporator to the amount of steam used to run the evaporator.

$$SE = \frac{m_{f,i} - m_{f,0} + \sum_{i=1}^{4} m_{v,i} + \sum_{i=1}^{3} m_{b,i}}{m_{v,0} + m_{v,c}} \tag{26}$$

The former is related to the revenue to be earned by the sugar factory. The latter is related to cost of producing raw sugar. It is, therefore, desirable for the sugar factory to maximize both parameters.

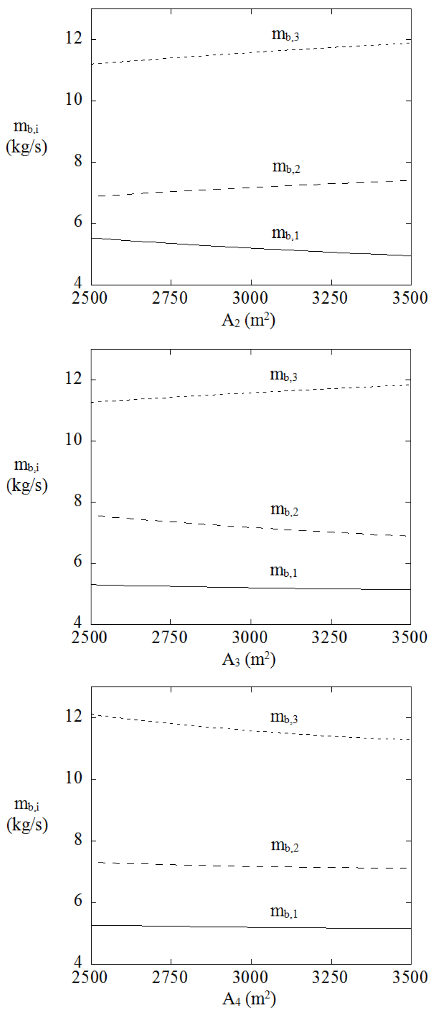
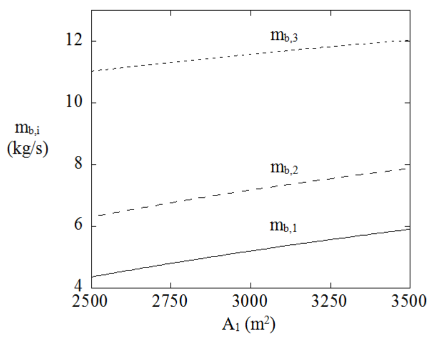


Figure 7. Variations of vapor bled from effects 1, 2, and 3 with surfaces of E1, E2, E3, and E4.



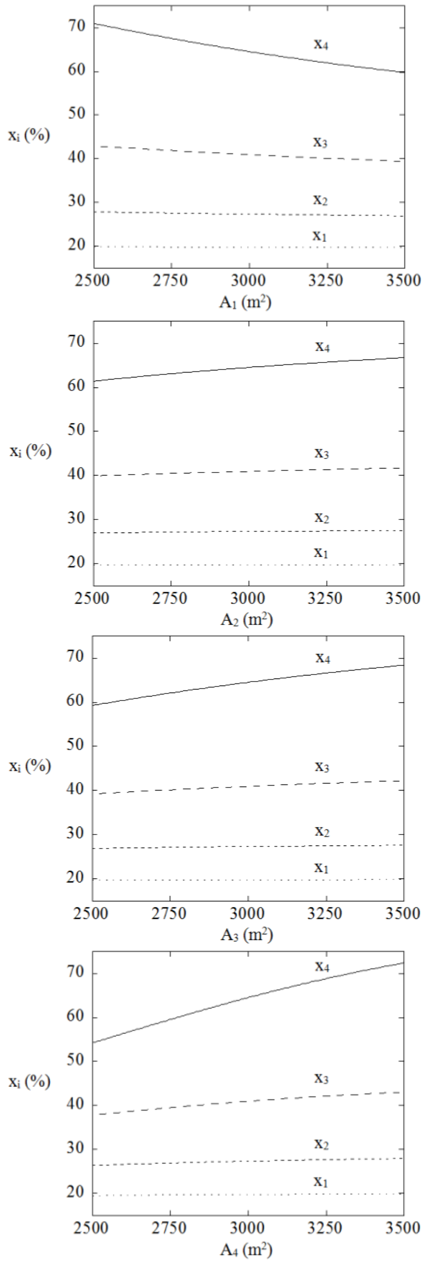


Figure 8. Variations of juice concentrations leaving effects 1, 2, 3, and 4 with surfaces of E1, E2, E3, and E4.

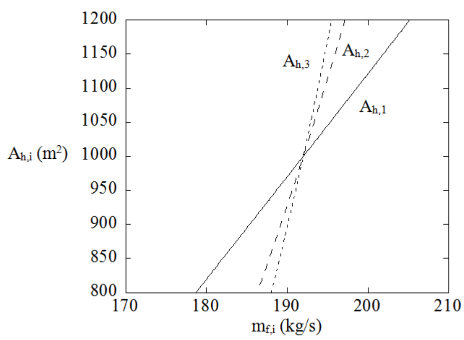


Figure 9. Effects of juice heater surfaces on sugar juice inlet flow rate.

Effects of juice heater surfaces on inlet sugar juice flow rate and steam economy are shown in Fig. 9 and Fig. 10, respectively. It can be seen that both parameters are more sensitive to $A_{h,1}$ than $A_{h,2}$ and $A_{h,3}$. It is also interesting to observe that increasing $A_{h,1}$ or $A_{h,2}$ produces opposite effects of increasing $m_{f,i}$ and decreasing SE. However, both parameters increase with $A_{h,3}$.

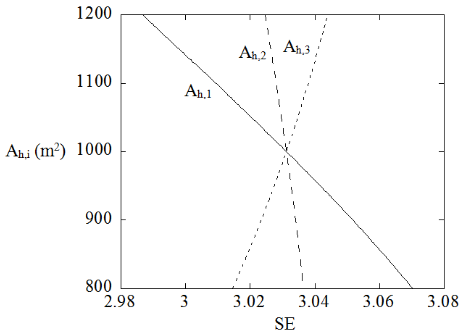


Figure 10. Effects of juice heater surfaces on steam economy.

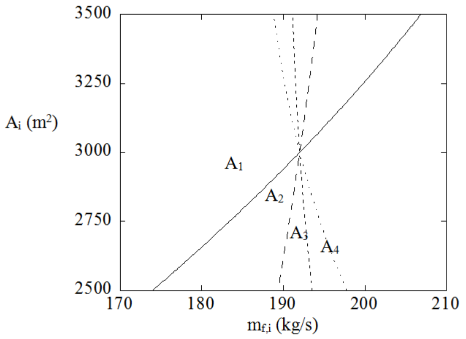


Figure 11. Effects of evaporator surfaces on sugar juice inlet flow rate.

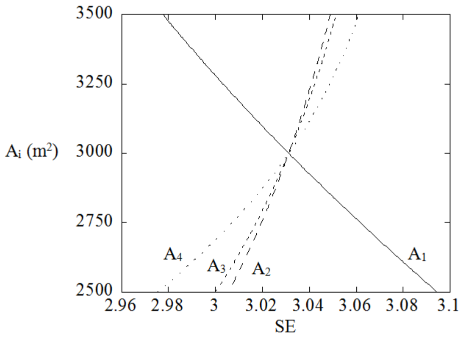


Figure 12. Effects of evaporator surfaces on steam economy.

Effects of evaporator surfaces on inlet sugar juice flow rate and steam economy are shown in Fig. 11 and Fig. 12, respectively. It can be seen that both parameters are more sensitive to A_1 than the other surfaces. It is also interesting to observe that increasing A_1, A_3 or A_4 produces opposite effects of increasing $m_{f,i}$ and decreasing SE. However, both parameters increase with A_2.

V. Conclusion

The model of quadruple-effect evaporator with vapor bleeding used to increase juice temperature to the saturation temperature in juice heater has been developed. This model is capable of evaluating the performance of the quadruple-effect evaporator subjected variations of juice heater surfaces and evaporator surfaces. Two performance parameters under consideration are the amount of sugar juice processed by the evaporator and the steam economy. It is found that both parameters are most sensitive to $A_{h,1}$ compared with the other juice heater surfaces, and most sensitive to A_1 compared with the other evaporator surfaces.

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