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Effect of vapor-bleeding and its configurations on multiple-effect sugarcane juice evaporator performance

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Abstract

Improving process performance is always important in any processing industry with the aim of reducing operation costs and improving the profit.Vapor bleeding may be used in processing industries using multiple-effect evaporatorsto reduces steam consumption and increases steam economyThe effect of vapor bleeding on separation performance using multiple-effect sugarcane juice evaporator was analyzed. The effect of increasing percent of vapor bled and determination of the most effective bleeding configuration in terms of energy efficiency and operating costs. The performance factors assessed were: steam requirement, total heat transfer area (A_t), steam economy, total utilized heat (Q_t), mass flow rate of bottoms (B_i), percent solids in the bottoms (X_{Bi}), and mass flow rate of vapors. To carry out this work, a five-effect evaporator, forward feed computer model was developed based on mass and energy balance equations, calibrated by data from steam tables. Simulations incorporating different configurations of vapor bleeding were carried out. Bleeding from each of the first four effects, E_i, and from a combination of effects (E_1&E_3, E_2&E_4) were carried out. The E_1&E_3 configuration showed a highest decrease in steam consumption by 23.73% and improved steam economy by 31.28%. Also, vapor bleeding reduced A_t and X_{Bi} while increasingB_i. This work suggests that to improve energy efficiency during separation of mixtures using evaporators, vapor bleeding should be practiced while maintaining a balance between vapors used to preheat the feed and that used for heating the subsequent effects.

*Keywords:*Multiple-effect evaporator, Vapor Bleeding, Steam economy and Sugar Industry evaporator, Mathematical modelling.

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1. Introduction

The evaporation unit in raw sugar manufacturing requires a large supply of thermal energy in order to remove a significant amount of water from the diluted sugar juice to produce sugar syrup (Chantasiriwan, 2017). The sugar juice is evaporated in the set of evaporator vessels known as multiple effects evaporators or evaporator station whereby steam is used in the first effect while evaporating vapors are used in the subsequent effects in the forward feed configuration (Khanam *et al*., 2008). Multiple-effect evaporator (MEE)consists of a number of pressure vessels operating at decreasing pressures (Chantasiriwan, 2017; Sorour, 2015; Khanam and Mohanty, 2010).

Chantasiriwan (2017) suggested to improve the process performance have mostly focused on the multiple-effect evaporator by adding more effects or more heating surface areas and selecting the optimum distribution of evaporator surface. In addition, the process performance can be enhanced by optimal operation scheduling of the evaporator and using the optimum tube dimensions for the evaporator. Another alternative to improve the process performance is the modification of the juice heater, which is another component of the juice evaporation process. This juice heater uses bled vapors as source of energy to raise temperature of the sugar juice before it enters the first effect.

Vapor bleeding is the technique in a multiple effect evaporator (MEE) systems in which vapor coming from the vapor space of an effect is divided into two streams, whereby one stream is used as heating medium in the subsequent effects and other part used for other appropriate purposes in the system. The latter is used to increase feed temperature in pre-heaters or increase liquor temperature in liquor re-heaters placed outside of subsequent effects depending on the MEE set up and feed configuration. Its capacity increases when the sugar juice temperature has been raised to near its boiling point (Chantasiriwan, 2017).The bled vapor can also be used as a heating medium in the crystallization unit of the sugar processing industry. The condensate of bled vapors can be flashed and the vapor generated from it can still be used as heating medium in the appropriate effects (Khanam and Mohanty, 2008).

Vapor bleeding is done to preheat the feed or liquor near to temperature of the effect it is entering into so that liquor can easily attain boiling temperature inside the effect. This increases evaporator capacity as a result steam consumption is reduced and steam economy improved (Bhargava et al., 2008a).Vapor bleeding not only reduces steam consumption and increases steam economy, but also it provides room for process improvement of the evaporation process (Srivastava et al., 2013). However, vapor bleeding comes with addition costs of installation and running heat exchangers in the evaporator station(Khanam and Mohanty, 2010;Yadav and Verma, 2020), giving more room for more research work on process performance and addition costs on vapor bleeding.

Several researchers had worked on simulation of multiple effect evaporators (Radovic *et al.,*1979; Pedro *et al.,* 1993; Bremford and Muller-Steinhagen, 1994; Kaya and Sarac, 2007; Lewis *et al.,* 2010; Jorge *et al.*, 2010; Bhargava et al., 2008c; Chantasiriwan, 2016) and developed models which take into account the interaction between the evaporator effects and juice pre-heater through mass and energy balances. They were then used to investigate the effects of additional juice heater surface and evaporator surface on the performance of the system. In the configuration reported, three juice heaters were incorporated and used vapor bled from the first three evaporator effects to raise juice temperature. A decrease in evaporator effects pressures with increase in heater surface areas, with pressure in the first effect being higher, and decreasing as you move to the next effect was reported. Using two heaters, their results showed an increase in bled vapors with increase in heater (1) surface area, with bled vapors from E3 being higher followed by vapors from E2 and lastly vapors from E1 being the lowest. However, an increase in heater (2) surface area increased with bled vapors from E2 and E3 while bled vapors from E1 decreased.The juice heater surface area affects the juice concentrations leaving E1, E2, E3 and E4.An increase in juice heater (1) surface area, liquor concentration increases from E1 to the last. However, liquor concentration leaving E4 decreased rapidly with an increase in heater (1) surface. Same trend is observed when juice heater (2) surface is increased.

Chantasiriwan (2017) determined optimum vapor bleeding arrangements for sugar juice evaporation process,a model taking into account interactions between multiple effect evaporator, juice heater and crystallizer, through mass and energy balances have also been reported First, they presented an increase in the steam economy with increase in the total juice heater surface for all the vapor bleeding arrangements in the three-effect and the four-effect vapor bleeding arrangement. Simulation results showed an increase in both the steam economy and the rate of processed sugar juice with increase in the total juice heater surface. In either three-effect or four-effect vapor bleeding arrangement, there is an optimum surface distribution that maximizes the steam economy. However, the two-effect vapor bleeding arrangement was found to be best as it yields a larger value of the rate of processed sugar juice than other vapor bleeding arrangements. It is the more suitable arrangement if maximizing the rate of processed sugar juice is the priority over maximizing the steam economy

In all this, an important aspect in vapor bleeding is its configuration in the evaporator station which adds value to the whole process. This study explore the effect of vapor bleeding on steam requirements, total heat transfer surface area requirements, total utilized heat, bottoms flow rate and composition, vapor mass flow rate, and steam economy.Bleeding configuration in this study is meant to indicate which effect or combinations of effects were bled for feed pre-heat. In this study, bleeding was implemented in the first, second, third and fourth effects (E1, E2, E3 or E4) separately or simultaneously on combined effects, in this case either E1&E3 or E2&E4. The aim was to determine which configuration leads to a better MEE performance. The performance of MEE was studied based on total surface area requirement for heat transfer, steam requirements, total vapor flow rate and steam economy.

2. Research Method

2.1 Model development

The five effects evaporator model was developed through excel computer package with the use of linear mass and energy balance equations. It was created from a three effects evaporator worked example and developed to a five-effect evaporator model. The model was calibrated by data from steam tables. The basis of the model was a feed rate of 500 kg/h of clear juice with 10% of solids from clarification and filtration stages of the sugar processing industry. A steam pressure of 300 kPa absolute was used to set up the five-effect evaporation system, while pressure in the last effect was kept at 60 kPa absolute. After completely solving the model, the simulation was conducted using the assumptions given in Table 1.

The feed configuration used in the model was forward feed. At first sensible heat was neglected but was later introduced in the simulation process of the model. Equations were developed from mass and energy balances and from graphical relationships of data from steam tables. The equations used specified and required variables. The five effects model was then changed to incorporate mass and energy balance equations for single and triple-effect models using same data, from which the results were compared. The effect of vapour bleeding and its configuration was studied as stated below.

Table 1. Variables used in modeling and simulation of the five-effect evaporator with assumptions made.

Variable	Set values
Feed rate, composition and temperature	F = 500 kg/h, X_f= 10% and T_f = 20°C
Pressure in the last effect, absolute	P_{V5} = 40, 60 and 80kPa
Steam pressure, absolute	P_S = 100 - 500 kPa
Product specifications	B_5 = 166.67 kg/h, X_{B5} = 30%, V_t = 333.33 kg/h
Overall heat transfer coefficient (U)	U_1= 3000, 2000, 1000 W/m^{2}K U_2= 2700, 1700, 700 W/m^{2}K U_3= 2400, 1400, 500 W/m^{2}K U_4 = 2100, 1100, 500 W/m^{2}K U_5 = 1800, 1000, 500 W/m^{2}K
Feed flow sequence	Forward feed, from E_1 to E_5
Bleeding fraction (%)	β_i= 0 – 0.75
Bleeding configurations	E1, E2, E3, E4, E1&E3 and E2&E4
Heat loss (%)	0 – 30%
Total number of effects	N = 5
Average specific heat capacity of juice	C_{pf} = 3.8209 kJ/kgK
Assumptions made:	
1)No boiling point elevation/rise (BPR)	
*2)*Equal heat transfer rates in each effect: $Q_1 = Q_2 = Q_3 = Q_4 = Q_5$	
3)Equal heat exchanger surface area (A_i) in all effects: $A_1 = A_2 = A_3 = A_4 = A_5$	
4)Quantities evaporated are equal in all effects and neglecting sensible heat.	

2.2 Five-effect evaporator process under bleeding conditions

A forward feed, five-effect system was modeled whereby, dilute/clear sugar juice enters the first effect at a known feed rate, proceed to the second effect, third, fourth and lasts to the fifth effect where sugar syrup is collected as final product before it is sent to the crystallization unit. Figure 1 shows the schematic diagram of the forward feed five effects evaporator system with heat exchange between bled vapors and the feed juice. Steam was only supplied in the first effect, where it evaporates the juice. The vapor from first effect is used to evaporate the juice in the second effect, and subsequently to the last effect, where the vapor is released to the environment. In Figure 1, five bleeding configurations are presented that is, bleed E1, bleed E3, bleed E4, bleed E1&E3 and bleed E2&E4. It also shows the heat exchanger that receives the cold feed juice and pre-heats it to its boiling temperature using bled vapors. The hot feed juice is then sent to the MEE first effect ready for the evaporation process. The heat exchange occurs as bled vapors from the station are fed to the heat exchanger which heats the cold juice and itself leaving the exchanger as condensate. Figure 1 shows dotted lines representing vapor stream while continuous line represents liquid or solution stream.

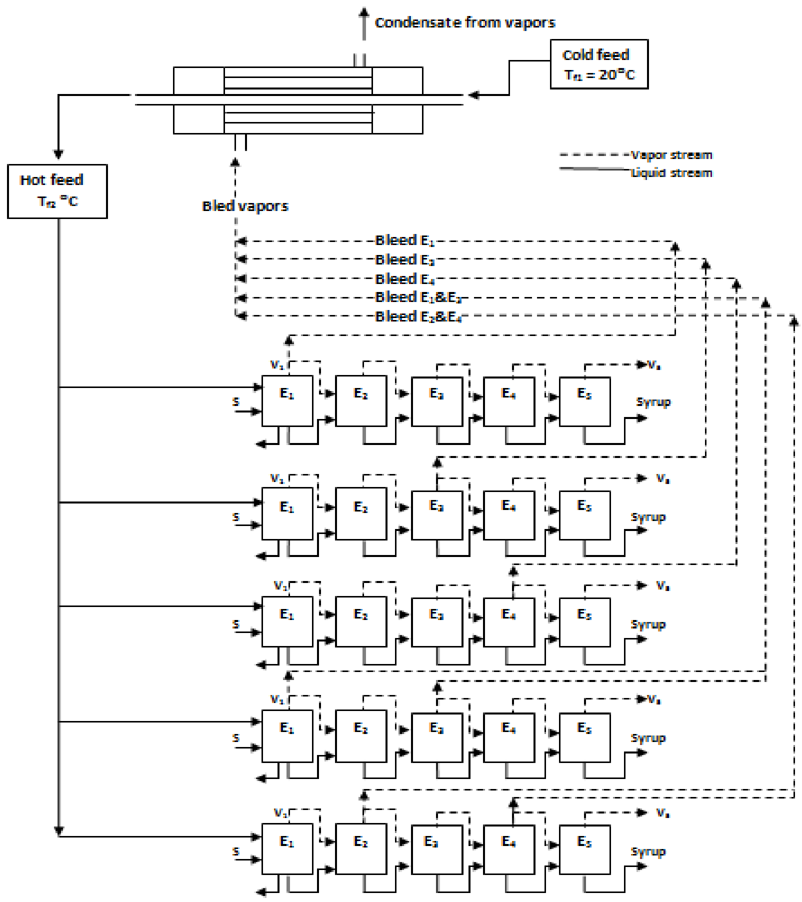


Figure 1. Five-effect evaporator station showing vapor bleeding configurations studied with heat exchange between bled vapors with the feed.

In this study, steam pressure was set at P_S = 300 kPa abs, while pressure in the last effect is kept at P_{V5} = 60 kPa abs. Given the feed temperature of the clear sugar juice at 20°C, the heat exchanger pre-heats the juice to its boiling temperature, T_{b1} as indicated in Figure 1. Vapors from E5 could not be re-used in the system and are released to the surrounding due to having lower temperature and pressure. From the developed model, vapors from E5 have the following properties, P_{V5} = 60 kPa abs, T_{b5}= 86.04°C and specific enthalpy of 2293.68 kJ/kg.

2.3 Algorithm for the model solution

Using mass and energy balance around all five effects of the system, a number of equations were formed. With the help of assumptions as mentioned above, the required variables were solved. Series of steps performed to obtain the required variables proceeds as follows:

Step 1: Values of known parameters were collected from specified parameters and parameters read from steam table. An initial guess of all U_i was made to start calculation.

Step 2: Overall solids balance to obtain mass flow rate of liquor in the final effect (B_5), was established as per Equation (1) (Bhargava et al., 2008a; Srivastava et al., 2013):

$$F.X_f = B_5.X_{B5} \tag{1}$$

Step 3: The overall mass balance was done to obtain total water vapor evaporated from all five effects (Khanam and Mohanty, 2008), leads to:

$$V_t = F - B_5 \tag{2}$$

Step 4: Solving for temperature drops across all effects, (ΔT_i), and assuming equal heat transfer in all effects McCabe et al., 1993; Coulson et al., 2002): $Q_1 = Q_2 = Q_3 = Q_4 = Q_5$, leads to:

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2 = U_3 A_3 \Delta T_3 = U_4 A_4 \Delta T_4 = U_5 A_5 \Delta T_5 \quad (3)$$

$$\Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4 + \Delta T_5 = T_s - T_{b5} \quad (4)$$

Also, equal heat transfer leads to $U_1 A_1 \Delta T_1 = U_i A_i \Delta T_i$, that is:

$$\Delta T_i = \left(\frac{U_1 \Delta T_1}{U_i}\right) \quad (5)$$

where i = 2, 3, 4 and 5.

Step 5: Equation (5) was substituted into Equation (4) to solve for ΔT_1:

$$\Delta T_1 = (T_S - T_{b5})/(1 + U_1/U_2 + U_1/U_3 + U_1/U_4 + U_1/U_5) \quad (6)$$

Step 6: ΔT_1 was used in Equation (5), to solve for ΔT_2, ΔT_3, ΔT_4, and ΔT_5. Boiling temperatures (T_{bi}) in all effects were then calculated Coulson et al., 2002; Al-Sahali and Ettouney, 2007):

$$T_{b1} = T_S - \Delta T_1 \quad (7)$$

$$T_{b2} = T_{b1} - \Delta T_2 \quad (8)$$

$$T_{b3} = T_{b2} - \Delta T_3 \quad (9)$$

$$T_{b4} = T_{b3} - \Delta T_4 \quad (10)$$

Step 7: Solving for steam requirement and steam economy.
Step 7a: Assuming quantities evaporated are equal in all effects and neglecting sensible heat Khanam and Mohanty, 2008:

$$V_1 H_{V1} = V_2 H_{V2} = V_3 H_{V3} = V_4 H_{V4} = V_5 H_{V5} = S H_S \quad (11)$$

$$V_1 + V_2 + V_3 + V_4 + V_5 = V_t \quad (12)$$

Step 7b: From Equation (11), making subject the quantities evaporated in each effect (V_i) and substituting in Equation (12), Equation (14) was obtained:

$$V_i = \left(\frac{V_1 H_{v1}}{H_{vi}}\right) \quad (13)$$

where i = 2, 3, 4 and 5.

$$V_1 + 0.99V_1 + 0.98V_1 + 0.97V_1 + 0.95V_1 = V_t \quad (14)$$

Step 7c: Using Equation (13) the quantities evaporated in each effect were determined. According to steam requirement (S) in kg/h was solved from Equation (15a) developed from (11).

$$S = \left(\frac{V_1 H_{v1}}{H_s}\right) \quad (15a)$$

Step 7d: Steam economy (SE) was then calculated from Equation (15b) as follows:

$$S.E = \left(\frac{V_t}{S}\right) \quad (15b)$$

Step 8: Solving for the bottoms (mass flowrate of liquor) from each effect (Bhargava et al., 2008a; Khanam and Mohanty, 2008;Srivastava et al., 2013), using mass balances around individual effects leads to solution for B_1, B_2, B_3 and B_4, that is:

$$B_1 = F - V_1 \quad (16)$$

$$B_2 = F - V_1 - V_2 \quad (17)$$

$$B_3 = F - V_1 - V_2 - V_3 \quad (18)$$

$$B_4 = F - V_1 - V_2 - V_3 - V_4 \quad (19)$$

Combining the four Equations (16), (17), (18), and (19); resulted in Equation (20):

$$\sum_{i=1}^{4} B_i = 4F - 4V_1 - 3V_2 - 2V_3 - V_4 \quad (20)$$

Step 9: To solve for percent solids of liquor in effects using solids balance around individual effects, Equation (21) and (22) were developed as suggested by different researchers (Bhargava et al., 2008a; Srivastava et al., 2013):

$$X_{B1} = \left(\frac{FX_f}{B_1}\right) \tag{21}$$

$$X_{Bi} = \left(\frac{B_{i-1}X_{Bi-1}}{B_i}\right) \tag{22}$$

where i = 2, 3, and 4.

Step 10: Based on the CSTR assumption for each effect, liquor exits the evaporator vessel at the temperature equal to the boiling temperature, that is, $T_{Bi} = T_{bi}$. Other required data were obtained from steam tables using the calculated liquor temperatures of all individual effects (T_{Bi}).

Step 11: The heat exchanger surface area of individual effects, A_i and total heat exchanger surface area required to evaporate the juice A_t were determined from heat balances around each effect as per Equation (23) for Effect 1, followed by Equation (24) and (25):

$$V_1 H_{v1} = Q = U_1 A_1 \Delta T_1 \tag{23}$$

$$A_1 = \left(\frac{V_1 H_{v1}}{U_1 \Delta T_1}\right) \tag{24}$$

$$A_t = A_1 + A_2 + A_3 + A_4 + A_5 \tag{25}$$

2.1 Solution of the Model with Vapor Bleeding, Sensible Heat and Heat Loss

Now with introduction of vapor bleeding from effect 1, 2, 3, and 4; and without neglecting sensible heat and heat loss, the model proceeds as follows:

Step 12: Vapor bleeding involved the use of bled vapors from each effect to raise the feed temperature in the heat exchanger. The initial feed temperature, T_{f1} was assumed to be 20°C. The vapor bleeding from each effect was ranged from 0 to 75% as presented in the analysis. From heat exchanger heat balance, the following Equations were developed:
Step 12 a: Considering each bleeding configuration was utilized separately, bleeding from Effect i:

$$V_{bi} H_{vi} = FC_{pf}(T_{f2} - T_{f1}) \tag{26a}$$

$$T_{f2} = T_{f1} + \left(\frac{V_{bi} H_{vi}}{F.C_{pf}}\right) \tag{26b}$$

where i= 1, 2, 3, and 4.
Step 12 b: Now, bleeding from E_1&E_3:

$$T_{f2} = T_{f1} + \left(\frac{V_{b1} H_{v1} + V_{b3} H_{v3}}{F.C_{pf}}\right) \tag{27}$$

Bleeding from E_2&E_4,

$$T_{f2} = T_{f1} + \left(\frac{V_{b2} H_{v2} + V_{b4} H_{v4}}{F.C_{pf}}\right) \tag{28}$$

where T_{f2} = New feed temperature after vapor bleeding

Step 13: Solving for the total heat which for now will include sensible heat in heating the juice from 20 to 126.57°C; latent heat of vaporization and heat loss which is assumed to be 5% of the sensible heat and latent heat of vaporization.
Step 13 a: The sensible heat in heating the juice from 20 to 126.57°C:

$$Q_{sh} = FC_{pf}(T_b - T_{f2}) \tag{29}$$

Step 13 b: The latent heat of vaporization was computed from Equation (30) (Khanam and Mohanty, 2008)2:

$$Q_L = V_1 H_{v1} \tag{30}$$

Step 13 c: The heat loss was calculated as follows (Srivastava et al., 2013):

$$Q_{loss} = \varepsilon(Q_L - Q_{sh}) \tag{31}$$

where ε = Percent heat loss.

Step 13 d: Solving for the total heat (Srivastava et al., 2013):

$$Q_t = Q_L + Q_{sh} + Q_{loss} \quad (32)$$

Step 14: The computations were then reworked for the new steam requirement; steam economy; and total heat transfer surface area, using the new total heat which has been influenced by sensible heat and vapor bleeding. Simulation of the model to study the effect of operating factors affecting performance of MEE system was done with consideration of calculations with sensible heat and vapor bleeding based on the model formulation above.

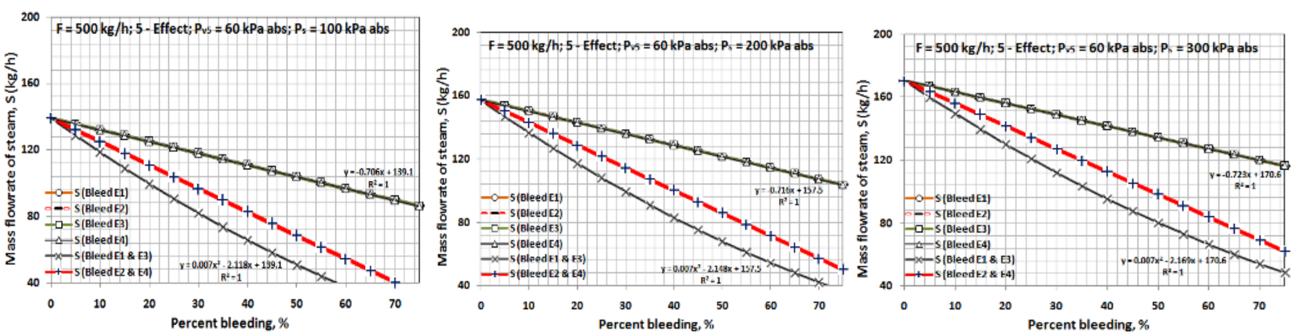
3. Results and Discussion

3.1. Variation of steam requirement with percent bleeding

On this first part, the model compares all bleeding configurations and determines the one with best performance in low steam requirement. Vapor bleeding allows proper heat utilization, whereas, a specified percent of the produced vapor from the effects is utilized for heating purposes in pre-heaters to raise feed juice temperature, in re-heaters to raise liquor temperature (mostly in backward and mixed feed configurations), and in crystallization unit (Srivastava et al., 2013).

Figure 2 (a-c) presents the variation of the steam requirement with percent bleeding, with model set up of N = 5, F = 500 kg/h, P_{V5} = 60 kPa absolute, for P_S = 100, 200 and 300 kPa abs respectively. Generally, when bled vapors are used to raise juice temperature in the feed at increasing percent bleeding, steam requirement of the whole system decreases. When the feed is at its boiling temperature, steam will only be used to evaporate water from it, rather than raising its temperature and later on evaporate water when its boiling temperature is achieved. This is an efficient energy utilization which results in low energy consumption (Khanam and Mohanty, 2008). However, increasing steam pressure from 100 to 300 kPa abs proves to increase the mass flow rate of steam in the system and hence increases energy consumption even without bleeding. Increasing P_S increases steam consumption from 139 to 170 kg/h at P_S = 100 and 300 kPa abs, respectively. With bleeding configuration of a combination of E_1 and E_3 (that is E_1&E_3), steam requirement of the five-effect evaporator system was reduced to the minimum for all bleeding percent as compared to other bleeding configurations.

Bleeding configurations were compared at varying percent bleeding and steam pressures of 100, 200 and 300 kPa abs, and among the six configurations used, a combination of E_1 and E_3 required lower amount of steam to evaporate the juice to the required syrup, with the reason that bled vapors from E_1 and E_3 contributes the most in raising feed temperature to its boiling point than other configurations. This implies that, E_1&E_3 lowers sensible heat required to raise the feed temperature to its boiling point inside evaporator E_1. As sensible heat contributes to the total utilized heat in evaporation process, reducing it will also lower the total utilized heat which is direct proportional to the steam requirement according to $S = Q_t/H_S$, thus reducing steam consumption in the system.



(a) (b) (c)

Figure 2. Variation of the steam requirement with percent bleeding in effects.

The effect of percent bleeding on steam requirement at varying steam pressure is presented in Figure 3(a-e). The use of bled vapors to pre-heat the feed juice proves substantial as it improves energy efficiency, increases evaporative capacity of the evaporator station and reduces steam consumption (Khanam and Mohanty, 2008;Srivastava et al., 2013). Generally, Figure 3 shows same trend for all bleeding configurations of a decrease in the required mass flow rate of steam with an increase in percent bleeding. However, an increase in steam pressure increases steam requirement in the system. Furthermore, bleeding configuration of a combination of E_1&E_3 follows a polynomial function of linear curves with the lowest minimum steam requirements at bleeding percent = 75%. This bleeding configuration shows the highest reduction in steam consumption. E_1 configuration and a combination of E_2&E_4 led to same results from the model, while configurations of E_3 and E_4 give same results also.

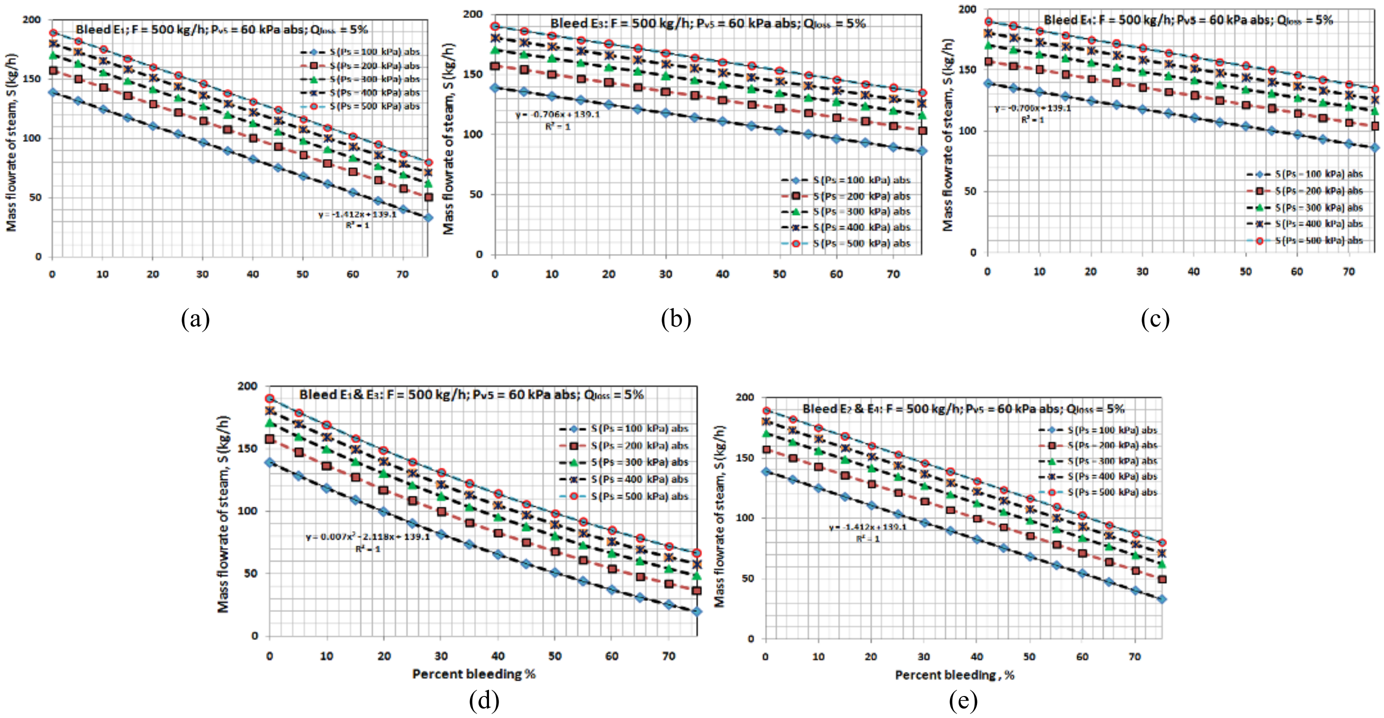


Figure 3. Variation of the required mass flow rate of steam with bleeding configurations.

With bleeding percent of 75%, a configuration of a combination of E1&E3 provides the least steam consumption which gives the highest ratio of steam consumption at 0% and 75% bleeding (S_0/S_{75}) as compared to other configurations as shown in Table 2. Therefore, in the five-effect evaporator system with incorporation of sensible heat, bleeding with a combination of E1&E3 proves most effective than other configurations in reducing steam consumption.

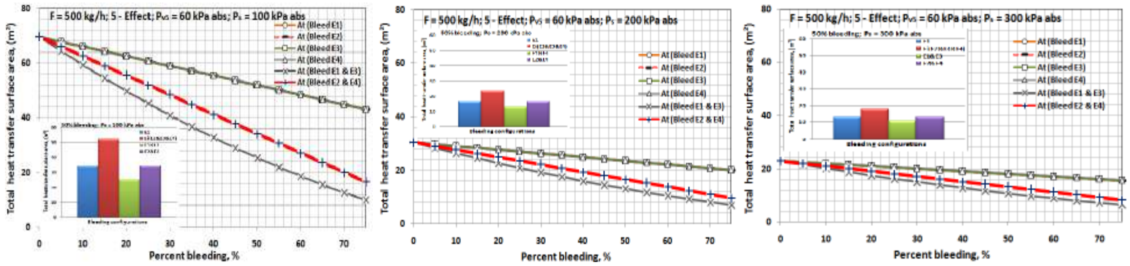
Table 2. Comparison of the ratio of steam consumption at 0% and 75% bleeding at different bleeding configurations.

Configurations	Bleed E1	Bleed E3	Bleed E4	Bleed E1&E3	Bleed E1
P_S (kPa abs)	S_0/S_{75}	S_0/S_{75}	S_0/S_{75}	S_0/S_{75}	S_0/S_{75}
100	4.19	1.61	1.61	6.98	4.19
200	3.14	1.52	1.52	4.29	3.14
300	2.74	1.47	1.47	3.51	2.74
400	2.53	1.43	1.43	3.13	2.53
500	2.37	1.41	1.41	2.86	2.37

3.2. Variation of the total heat transfer surface area with percent bleeding

When modeling data shows that the required total heat transfer area for evaporation is lower than the pre-established value, it implies that the performance of the evaporator is improved. The variation of the total heat transfer surface area with percent bleeding in effects is shown in Figure 4. In the plots, bleeding configurations are compared with the aim to find the one with higher performance in terms of reducing the total heat transfer surface area required to evaporate the juice from 10% solids to 30% solids sugar syrup. Vapor bleeding improves energy efficiency in the system as it allows the produced vapors to be used for different purposes in the plant including pre-heating the feed (Srivastava et al., 2013).

Generally, an increase in percent bleeding in the effects decreases the required total heat transfer surface area which means proper utilization of the available energy. Figure 4 (a-c)show that, bleeding configuration of a combination of E1&E3 provides the least required total heat transfer surface area followed by a combination of E2&E4. The bleeding combination of E1&E3 shows a downward curve in all steam pressures whereas other bleeding configurations show linear decrease in the required total heat transfer surface area. Furthermore, an increase in the steam pressure shows a decrease in the required total heat transfer surface area, which means that the overall temperature difference driving force has been increased in the system due to higher steam saturation temperature at higher pressure.Therefore, as shown in Figure 4, using bled vapors in pre-heating the feed juice is a proper utilization of the available energy in the system and proves cost effective in operation as the total heat transfer surface area required to evaporate the juice is reduced.



(a) (b) (c)

Figure 4. Variation of the required total heat transfer surface area with percent bleeding in effects.

At 0% bleeding, all graphs start at the same values of A_t for a given steam pressure but as percent bleeding increases different total area requirements were observed for each bleeding configuration. The A_t decreased faster for bleeding configuration E_1&E_3 compared to other configurations. Also, at the same steam pressure of 100 kPa abs, keeping all other conditions constant the total area requirement, (A_t) was highest and decreases faster with percent bleeding. However, while A_t drops faster with percent bleeding for bleeding in E_1, the effects of bleeding in E_2, E_3, and E_4 alone are similar as shown in Figure 4. But a combination of E_1&E_3 has a stronger effect on lowering A_t than E_i alone and also compared to E_2&E_4 configuration.

The variation of the total heat transfer surface area requirements with percent bleeding and its configuration is presented in Figure 5 for five different steam pressures. The analysis was done with the setup of F = 500 kg/h, P_{V5} = 60 kPa absolute, and heat loss = 5%. In general, all the graphs in Figure 5 show a decrease in the required total heat transfer surface area with increase in percent bleeding from all effects. Increasing steam pressure from 100 to 500 kPa absolute decreases the total heat transfer surface area. Steam pressure, P_S = 100 kPa absolute behaves differently from other steam pressures, it gives much higher total heat transfer surface area requirements than other settings. A combination of E1&E3 gives the lowest total heat transfer surface area than other configurations. The configuration Ei and combination of E2&E4 gives similar results, while also configurations of E3 and E4 give similar results. Therefore, in the five-effect evaporator system with incorporation of sensible heat and heat loss, bleeding with a combination of E1&E3 proves most effective than other configurations.

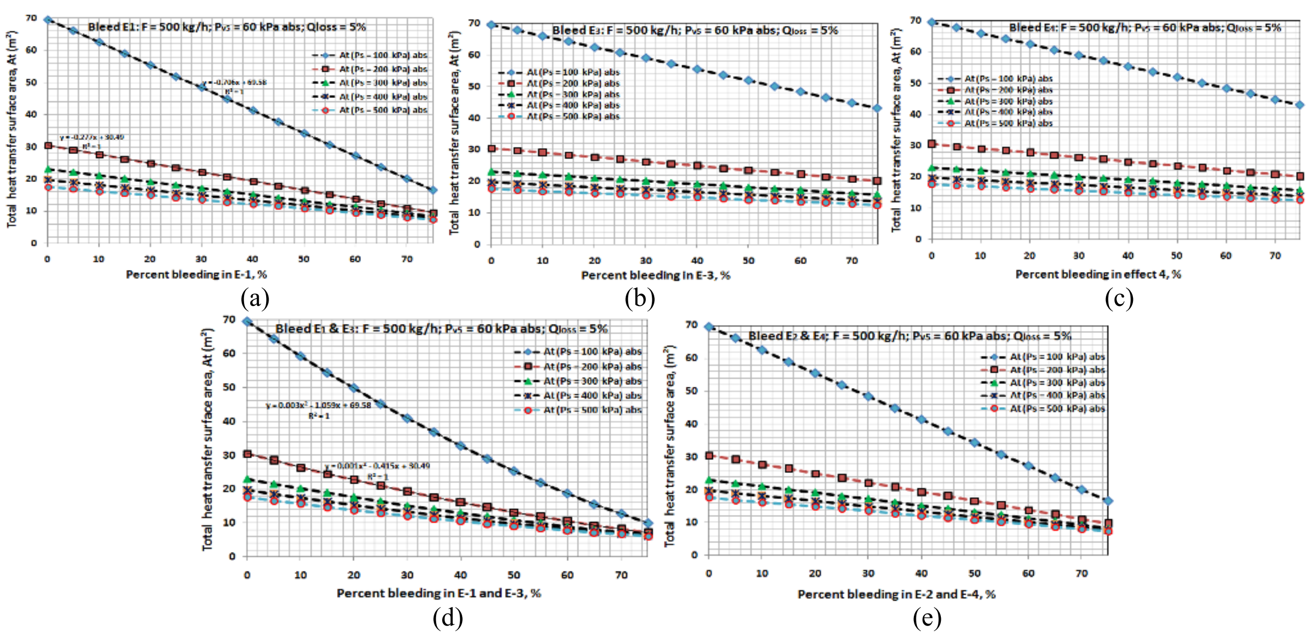


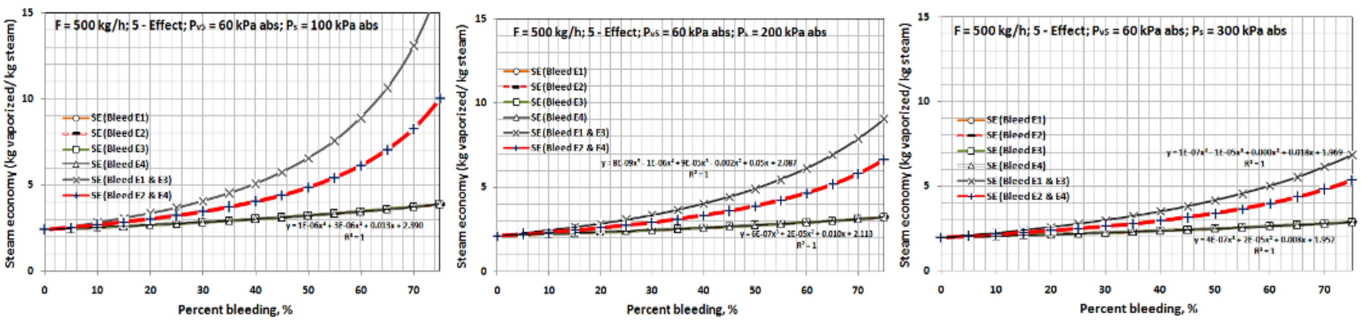
Figure 5. Variation of the required total heat transfer surface area with bleeding configuration.

The results in Figure 5 shows also that the area requirements for MEE (5-E) is very sensitive to bleeding of vapors at a lower steam pressure of 100 kPa abs for which A_t dropped from 70 m^2 to 20, 45, 45, 10 and 17 m^2 when bleeding in E1, E3, E4, E1&E3 and E2&E4 respectively. For a bleeding configuration of a combination of E1&E3 the A_t variation with percent bleeding follows a polynomial function of order 2, while the rest of configurations have linear functions. This shows that E1&E3 configuration will lead to higher performance of MEE since the total area requirements drops faster for P_S = 100 kPa abs, and P_{V5} = 60 kPa abs.

3.3. Effects of bleeding on steam economy in a five-effect evaporator system

Several configurations were used including combinations as shown in Figure 6. Steam economy as the ratio of the total water vaporized from the system to the steam consumption, is inversely proportional to steam consumption. That means, an increase in the steam consumption reduces steam economy (Srivastava et al., 2013). Vapor bleeding for use in preheating the feed will reduce the steam consumption based on which the steam economy is affected. The variation of steam economy with percent bleeding in effects is presented in Figure 6 where bleeding configurations are compared to find the one with higher performance in increasing the steam economy of the system.

Generally, increasing percent bleeding in effects increases steam economy of the whole system as steam consumption is reduced to the minimum depending on how much percent of the bled vapors is sent to pre-heat the feed. In this study, the percent bleeding was varied from 0 to 75% for use in pre-heating the feed. Configurations with combinations of E1&E3 and E2&E4 show curves which follow similar trend. Furthermore, Figure 6 shows that, a combination of E1&E3 shows the highest values of steam economy for a given percent bleeding as compared to other configurations. The increase in steam economy for E1&E3 increases system performance higher than the rest of configurations. Considering a graph with P_S = 200 kPa abs, a configuration of a combination of E1&E3 follows a polynomial function of order 5 higher than other configurations, which proves a higher performing configuration in the MEE.



(a) (b) (c)

Figure 6. Variation of steam economy with percent bleeding in effects.

While the steam consumption is lower at P_S = 100 kPa abs, yet steam economy values are higher compared to those at P_S = 200 and 300 kPa abs. Thus, vapor bleeding in combination with lower steam pressure will lead to higher SE or good MEE performance. Taking an example of 30% bleeding for each configuration, Table 3 compares the values of SE achieved for five-effect MEE system at different P_S. Based on Table 3, it is evident that higher values of steam economy were observed for E1&E3 combination in all steam pressures.

Table 3. Steam economy values at different steam pressure for 30% bleeding and bleeding configurations.

Bleeding configuration	P_S = 100 kPa abs	P_S = 200 kPa abs	P_S = 300 kPa abs
E1	3.62	3.05	2.75
E3	2.97	2.57	2.35
E4	2.97	2.57	2.35
E1&E3	4.27	3.52	3.12
E2&E4	3.62	3.05	2.75

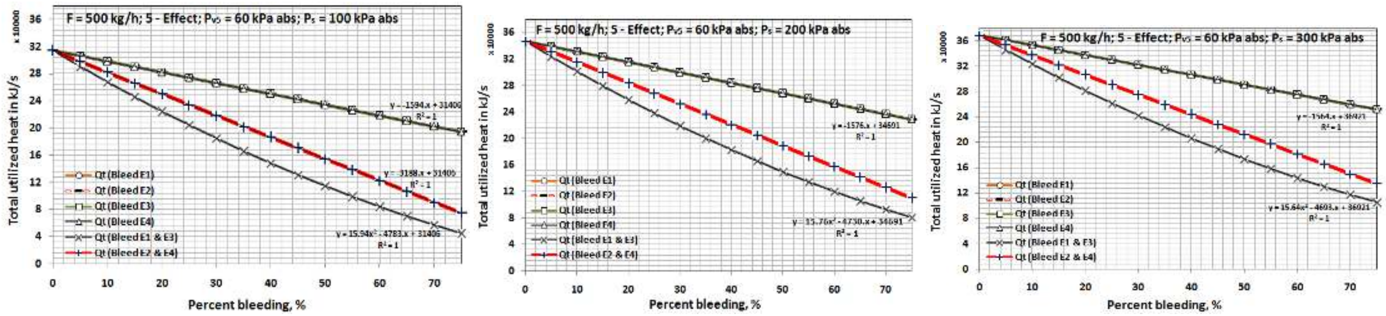
Therefore, with a higher performing bleeding configuration in a combination of E1&E3, the steam economy is improved and a higher system performance is achieved. Process improvement in terms of improving steam economy is achieved with a good design of feed pre-heater in a combination selection of effective bleeding configuration such as E1&E3, as compared to other bleeding configurations.

3.4. Effect of bleeding on the total utilized heat in the evaporator station

The total utilized heat is composed of sensible heat used to raise the temperature of the juice from its normal temperature to its boiling temperature, the latent heat of vaporization, and heat loss from effects to the surrounding (Khanam and Mohanty, 2008). Effect of increasing percent bleeding on the total utilized heat in an evaporator station is presented in Figure 7. Analysis was set at N = 5, F = 500 kg/h, P_{V5} = 60 kPa abs, and P_S = 100 - 300 kPa abs. Generally, increasing percent bleeding decreases the total utilized heat in the system as shown in Figure 7. Figure 7 shows that, increasing steam pressure increases the total utilized heat in the system, where with P_S = 100 kPa abs, 0% bleeding, graphs started at 320 MW; with P_S = 200 kPa abs, 0% bleeding, graphs started at 340 MW and with P_S = 300 kPa abs, 0% bleeding, graphs started at 360 MW. The lower the total utilized heat for running the whole MEE, the higher the performance.

For a bleeding configuration of a combination of E1&E3, the total utilized heat variation with percent bleeding follows a polynomial function of a second degree, while the rest of configurations have linear decreasing functions. This shows that, E1&E3

configuration leads to higher performance of MEE since the total utilized heat was lowest for all the values of steam pressure and percent bleeding.



(a) (b) (c)

Figure 7. Variation of the total utilized heat in evaporation with percent bleeding in effects.

Therefore, as increasing percent bleeding decreases the total utilized heat in the system, increasing feed pre-heating with the increased bled vapors, the system will not require very high amount of heat in order to evaporate the sugar juice. The sensible heat in raising feed juice temperature to its boiling point has been largely reduced by bled vapors. This will result in reduction in steam consumption and improvement in steam economy as well as process performance improvement. Furthermore, configuration with a combination of E1&E3leads to higher performance of MEE since the total utilized heat drops faster for all the steam pressures.

3.5. Variation of the mass flow rate of liquor with bleeding

During evaporation, water is removed from the feed juice to form a concentrated juice as the juice moves from first effect to the last where most concentrated liquor (syrup) is collected. Where bleeding is utilized, vapor from the juice is collected and used as a heating medium in the subsequent effects of the evaporator station (Khanam and Mohanty, 2008;Srivastava et al., 2013). Increasing percent bleeding has an effect on the mass flow rate of liquor in the system Figure 8 shows how mass flow rate of liquor varies in E1, E2, E3 and E4 with an increase in percent bleeding. Results show that, liquor mass flow rate is only affected by bleeding in the respective effects where bled vapors have been utilized. However, in the respective effect of the evaporator system that bled vapors have been utilized in the feed pre-heating process, they all show same trend of an increase in the mass flow rate of liquor with increase in percent bleeding. Furthermore, bleeding in E1 is affecting the whole evaporator system, as shown in Figure 8 (a-d) because E1 is the one that receives the steam and produces the first vapors with higher pressure and temperature that provides heating in the subsequent effects. Thus, when E1 vapors are utilized in bleeding the whole system gets affected in liquor flow rate.

The bottoms flow rate from the last effect, B_5, was not affected since it was fixed during model development. As shown in Table 4, B_1 is affected by two bleeding configurations bleed E1 and bleed E1&E3, while others do not show any changes. The bottoms flow rate, B_2, was affected by bleeding configurations, bleed E1, bleed E2, bleed E1&E3 and bleed E2&E4. B_3 was affected by bleeding configurations, bleed E1, bleed E2, bleed E3, bleed E_1&E_3 and bleed E2&E4. While B_4 was affected by all the bleeding configurations. Comparing all the bleeding configurations used, bleed E1&E3 is the one that increases the mass flow rate of liquor to the maximum for all effects than others. Therefore, increase in percent vapor bleeding increases the mass flow rate of liquor but in respective effects of the evaporator system that bled vapors have been utilized in the feed pre-heating process, whereas bleeding configuration bleed E1 affects the whole evaporator system because E1 is the one that receives the steam and produces the first vapors with higher pressure and temperature that provides heating in the subsequent effects. However, comparing all the bleeding configurations, a combination of E1&E3 increases the mass flow rate of liquor to the maximum than others.

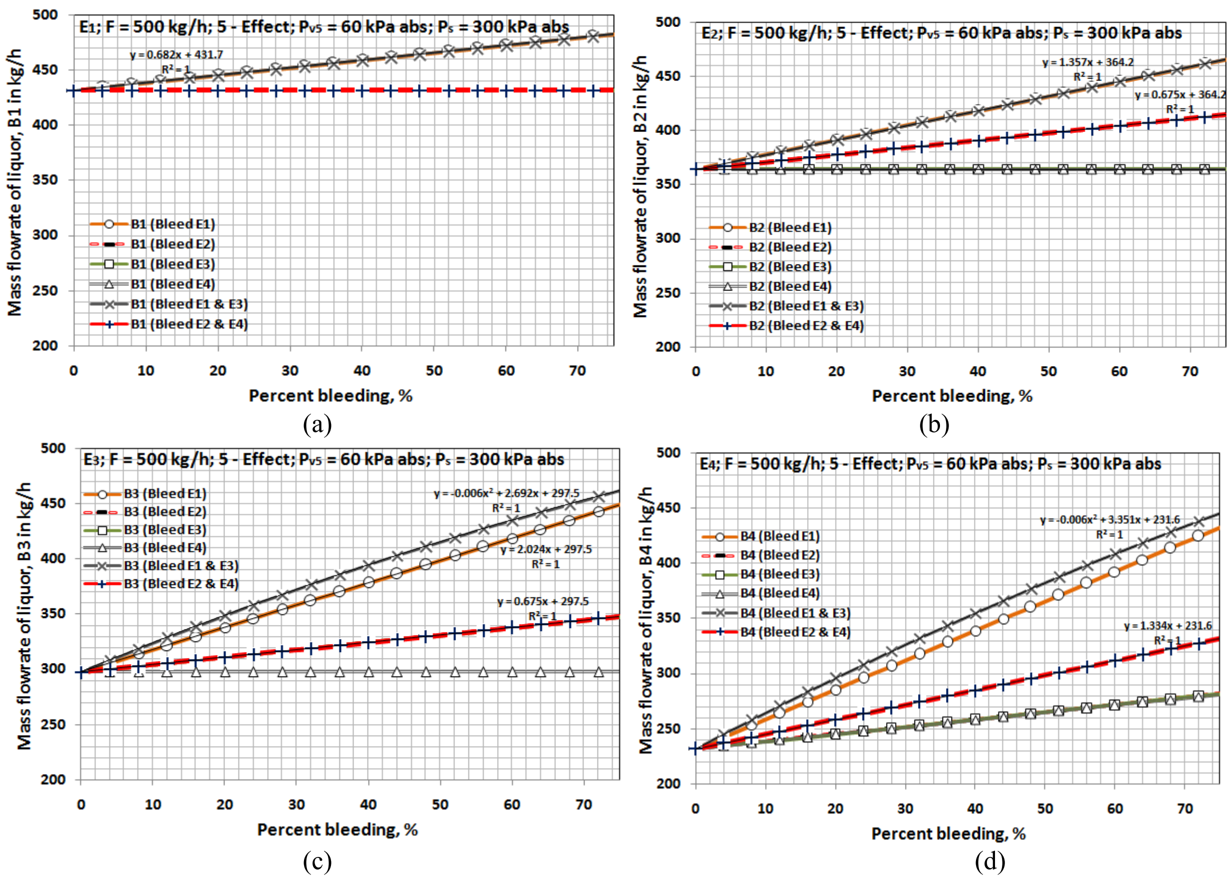


Figure 8. Variation of the mass flow rate of liquor, B_i with percent bleeding.

Table 4. Identified liquor and vapor properties affected by different bleeding configurations

Bleeding configuration	*Effect 1*			*Effect 2*			*Effect 3*			*Effect 4*			*Effect 5*		
	B_1	X_{B1}	V_1	B_2	X_{B2}	V_2	B_3	X_{B3}	V_3	B_4	X_{B4}	V_4	B_5	X_{B5}	V_5
E1	√	√	√	√	√	√	√	√	√	√	√	√	-	-	√
E2	-	-	-	√	√	√	√	√	-	√	√	-	-	-	-
E3	-	-	-	-	-	-	√	√	√	√	√	-	-	-	-
E4	-	-	-	-	-	-	-	-	-	√	√	√	-	-	-
E1&E3	√	√	√	√	√	√	√	√	√	√	√	√	-	-	√
E2&E4	-	√	-	√	√	√	√	√	-	√	√	√	-	-	-

3.6. Effect of vapor bleeding on the solids concentrates in the liquors (X_{Bi})

As evaporation process proceeds, the final product from the final effect is the concentrated sugar syrup after the removal of water from the juice fed in the first effect. Steam is used to evaporate water from the juice and percent solids increases from first to the last effect (Khanam and Mohanty, 2008). Figure 9 presents the variation of the percent solids of liquor in effects, X_{Bi} with percent bleeding. In all effects, X_{Bi} decreases with percent bleeding depending on configuration as shown in Table 4. It was observed that X_{B5} was not affected since it was fixed during model development. However, Table 4 shows that, X_{B1}, X_{B2}, X_{B3} and X_{B4} are all affected by the configuration bleed E1, because it's the first effect and receives the steam; its vapor is at higher temperature and pressure than other effects, these vapors heat the subsequent effects in the system.

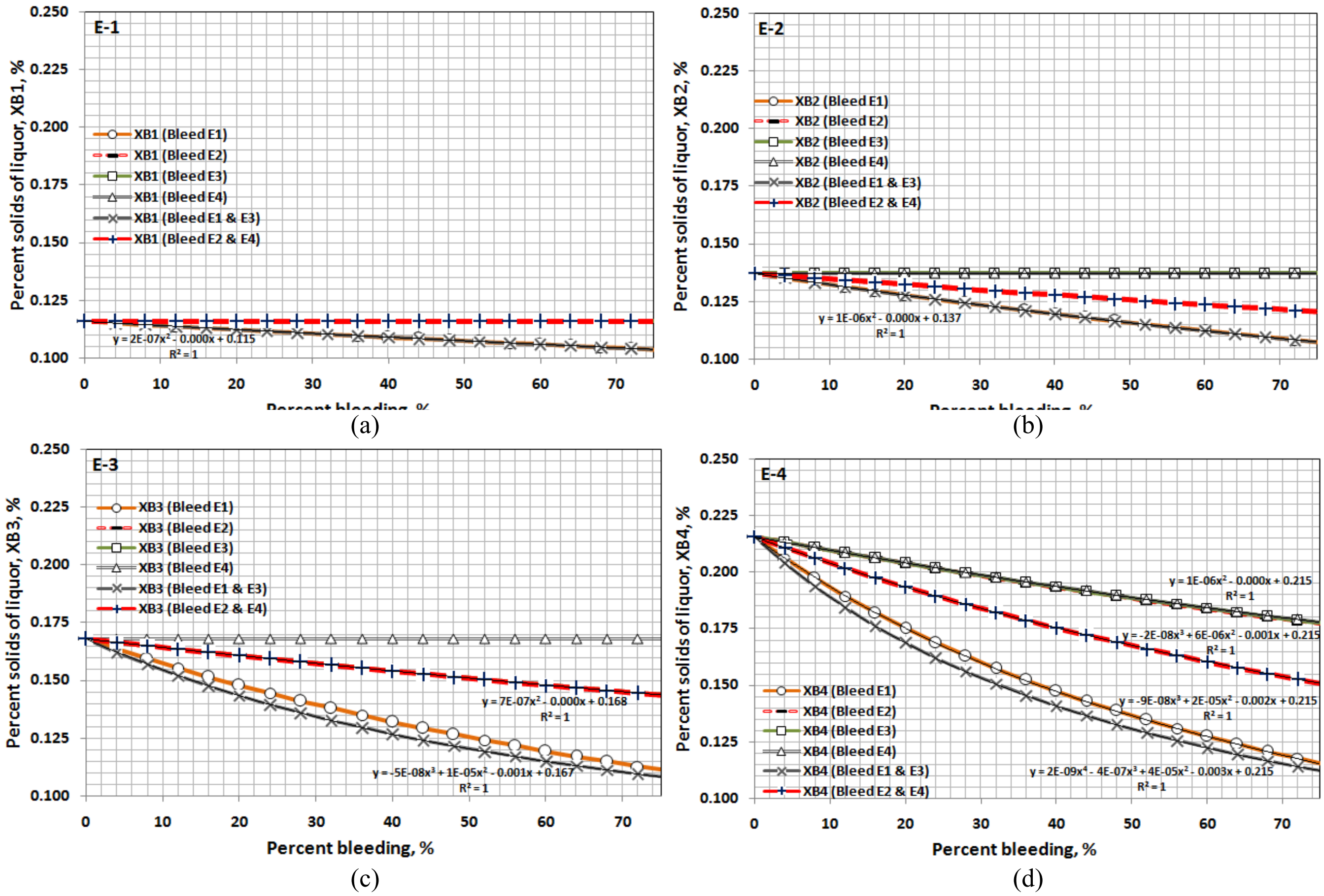


Figure 9. Variation of the percent solids of liquor in effects, X_{Bi} with percent bleeding (P_{V5} = 60 kPa abs, P_S = 300 kPa abs)

Furthermore, analysis in Table 5 shows that, X_{B1} is affected by two bleeding configurations bleed E_1 and bleed E1&E3, while others do not show any changes. X_{B2} is affected by bleeding configurations, bleed E1, bleed E2, bleed E1&E3 and bleed E2&E4. X_{B3} is affected by bleeding configurations, bleed E1, bleed E2, bleed E3, bleed E1&E3 and bleed E2&E4. While X_{B4} is affected by all the bleeding configurations. Therefore, as shown in Figure 9, with the present model, an increase in percent bleeding decreases percent solids of liquor in effects. Moreover, bleeding configuration of a combination of E1&E3 performs more than other bleeding configurations in reducing percent solids of liquor in effects with increase in percent bleeding. Thus, bleeding has a disadvantage of dilution of syrup, that is, lowers solids concentration, $X_{Bi.}$

3.7.Effect of bleeding on mass flow rate of vapors

The variation of the mass flow rate of vapor with percent bleeding at varying bleeding configurations is presented in Figure 10 with model set up of F = 500 kg/h, N = 5, P_{V5} = 60 kPa abs and P_S = 300 kPa abs. Vapors from an evaporator effect are a result of evaporation process on clear sugar juice to form sugar syrup in the final effect. An increase in number of effects in the evaporator station from single to multiple effect system is considered improving energy efficiency and effectiveness because in MEE systems, produced vapors are used as heating medium in the subsequent effects and therefore reduces steam consumption, improves steam economy and maximizes system performance (Khanam and Mohanty, 2008;Srivastava et al., 2013; Chantasiriwan, 2017). Generally, vapor bleeding from evaporator system means rather than using whole of the produced vapor in heating the subsequent effects, percent of it is used in other purposes like pre-heating the feed juice, and therefore the vapor that proceeds in the line get reduced. Figure 10 shows that, the mass flow rate of vapor is affected in effects where bleeding has happened and vapors connected to other effects, example, E1.

As shown in Table 4, V_1 is affected by bleeding configurations, bleed E_1 and bleed E_1&E_3. V_2 is affected by bleed E1, bleed E2, bleed E1&E3 and bleed E2&E4.V_3 is affected by bleed E1, bleed E3 and bleed E1&E3. However, V_4 is affected by bleed E1, bleed E4, bleed E1&E3 and bleed E2&E4. While V_5 is affected by bleed E1 and bleed E1&E3. Table 4 summarizes the vapor flow rates affected by different bleeding configurations. They all show a decrease in the mass flow rate of produced vapor with increase in percent bleeding. This means that, as bleeding improves energy efficiency in the evaporator system, it should be done in a balanced way that the system remains with enough vapor to heat the subsequent effects in the station. Also there should be a balance between bled vapors and the need to concentrate the syrup, since V_i drops due to bleeding.

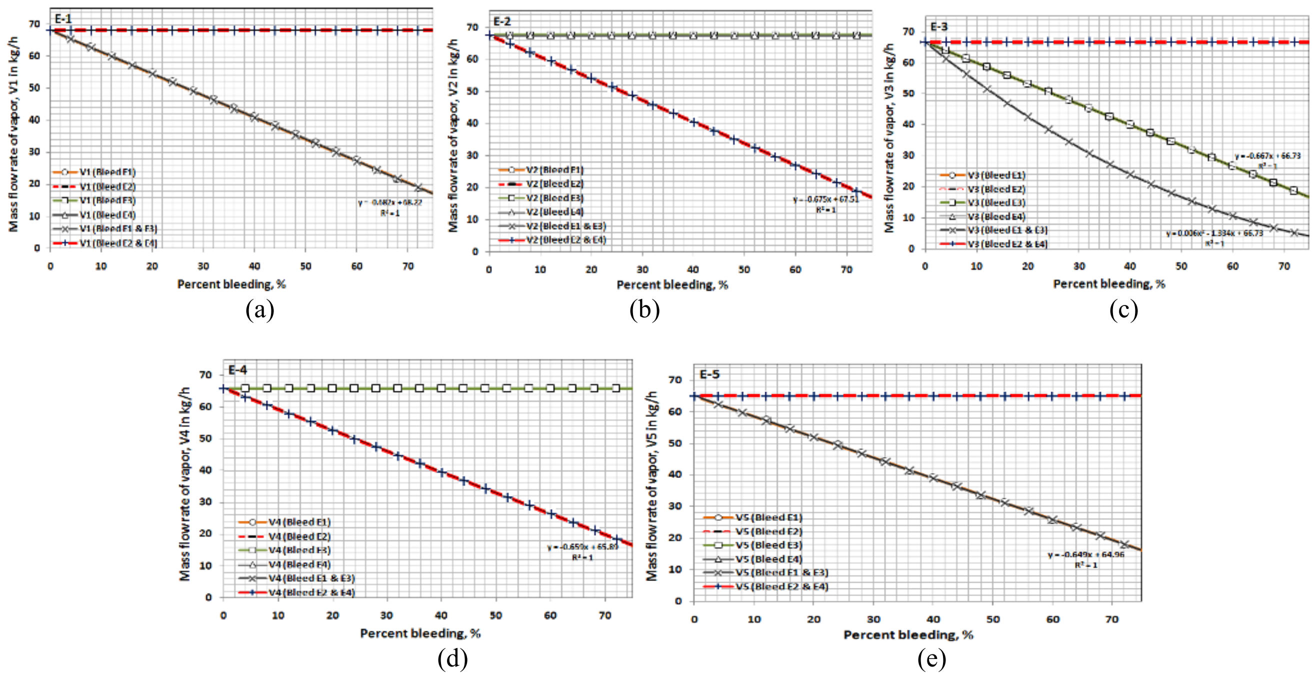


Figure 10. Variation of the mass flow rate of vapor, V_i with percent bleeding (P_{V5} = 60 kPa abs, P_S = 300 kPa abs)

3.8.Effect of other parameters on MEE operated with bleeding

a) Effect of feed rate on steam requirement for different bleeding configurations

Feed rate or plant capacity is proportional to the steam requirement such an increase in the feed rate will also increase the steam consumption in the system. However, when vapor bleeding configurations are applied to the MEE, steam requirement decreases compared to operations without bleeding (Chantasiriwan, 2017). The variation of the required mass flow rate of steam with feed rate at varying bleeding configurations is presented in Figure 11. A linear increase in mass flow rate of steam as mass flow rate of feed increases was observed for all bleeding configurations. The graphs start from a common point and widen apart as feed rate increases meaning appreciable effects of bleeding is much seen in large scale than small scale.

Bleeding from E1, E3, E4, combination of E1&E3, and E2&E4 reduces steam consumption. However, the configuration that reduces steam consumption the most with an increase in feed rate is bleeding from a combination of E1&E3 as shown in Figure 11. This configuration is followed by bleeding from E1 and combination of E2&E4 in which steam consumption is reduced by same amount. It is also observed that, bleed E3 and E4 gives same effect. Therefore, as noted from Figure 11, an increase in feed rate or plant capacity increases steam requirement in the system, but bleeding will reduce the effect by decreasing steam consumption. A bleeding configuration by a combination of E1&E3 maximizes system performance as it reduces steam consumption with higher amount than other configurations, see Figure 11.

b) Effect of pressure in the last effect on steam requirement for different bleeding configurations

The overall temperature difference of the evaporator system is influenced by the increase or decrease in pressure in the last effect and steam pressure. An increase in the pressure in the last effect increases T_{b5} and hence reduces the overall temperature difference of the system which is the driving force in evaporating the juice and vice versa (Khanam and Mohanty, 2008; Srivastava et al., 2013). The effect of increasing pressure in the last effect on the required mass flow rate of steam is presented in Figure 11 where the effects of bleeding configurations are also compared. All the graphs in Figure 11 follow similar trend of an increase in the required mass flow rate of steam to a maximum point with increase in pressure in the last effect. Figure 11 also shows that, bleeding reduces the required mass flow rate of steam in the system. With a bleeding configuration of a combination of E1&E3, steam consumption is reduced to the minimum compared to other configurations. Figure 13 also show that bleed E3 and bleed E4 gives similar results while bleed E1 and a combination of E2&E4 also gives similar results.

While an increase in pressure in the last effect of the MEE system might be done to restore the reduced heat transfer coefficient due to fouling, the increase in P_{V5} will reduce the overall temperature difference of the whole system and reduce the evaporative capacity (Peacock, 2007). Since the increase in pressure in the last effect increases the steam requirement of the system in order to compensate for the reduced temperature difference, vapor bleeding will reduce the sharp increase in the steam requirement of the system, as shown in Figure 11.

c) Effect of feed rate on total heat transfer surface area under different bleeding configurations

With proper energy consumption in the evaporator station, the total heat transfer surface area required to evaporate the juice is reduced and costs of installation of an extra heat transfer area are lessened. When such information is generated from simulation it implies that the existing evaporator performance has improved. With bled vapors used to pre-heat the feed juice, the first effect of the evaporator station receives the hot feed near or at its boiling temperature which allows evaporation process to start instantly. This improves evaporative capacity of the MEE system (Chantasiriwan, 2016). Figure 11shows that, an increase in plant scale necessitates the need of an increase in the required total heat transfer surface area. However, proper energy utilization in vapor bleeding reduces that sharp increase in the heat transfer area requirement. The graphs in Figure 11start from a common point and widen as the scale increases meaning appreciable effects of bleeding is much seen in larger scale than small scale.

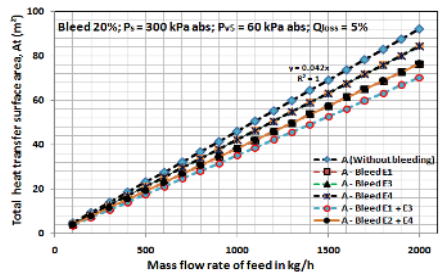


Figure 11. Effect of vapour bleeding and its configuration on: a) steam requirements vs. feed flow rate, b) steam requirements vs. pressure in the last effect, and c) total heat transfer surface area vs. feed flow rate .

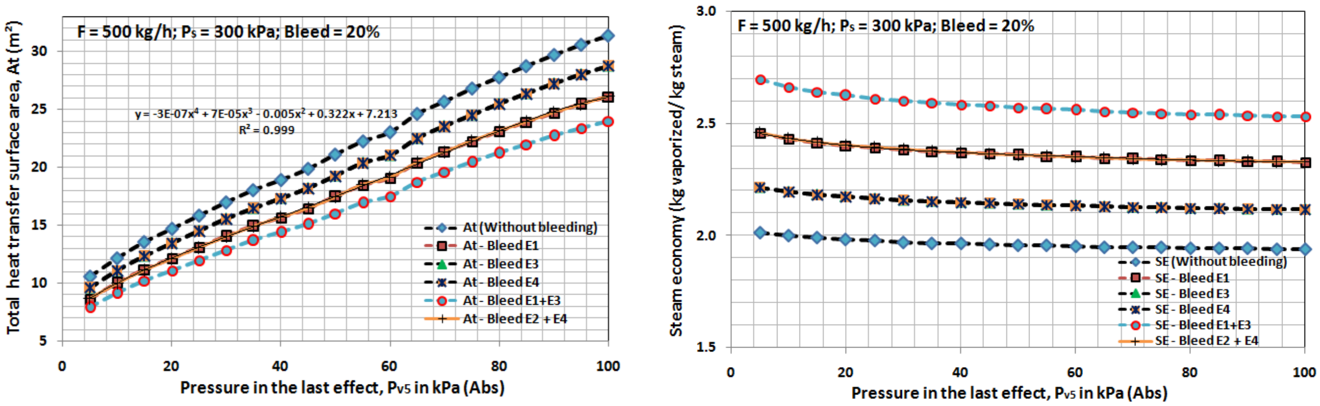
Figure 11 shows that, when vapor is bled out, it reduces the required total heat transfer surface area in the system. Bleeding from E1, E3, E4, combination of E1&E3, and E2&E4 reduces the total heat transfer surface area requirements. The configuration that reduces the heat transfer surface area the most is bleeding by a combination of E1&E3 as shown in Figure 11. This configuration is followed by bleed E1 and combination of E2&E4 in which the total heat transfer surface area requirements is reduced by same amount. It is also observed that, bleed E3 and bleed E4 give similar results.

Therefore, in a five-effect evaporator system, an increase in the plant scale necessitates the need to increase the total heat transfer surface area required to evaporate the juice. But when bleeding is incorporated in the system, it reduces the effect of sharp increase in the total heat transfer surface area. Moreover, a bleeding configuration of a combination of E1&E3 reduces the required total heat transfer surface area more than other configurations in the system and therefore maximizes its performance the most.

d) Effect of pressure in the last effect on the total heat transfer surface area requirements for different bleeding configurations

An increase in pressure in the last effect decreases the overall temperature difference and reduces the evaporative capacity of the system meaning that it reduces system performance. Thus, there is a need to increase total heat transfer surface area required to evaporate the juice to syrup in order to restore or maximize system performance (Peacock, 2007). Incorporation of vapor bleeding in the system improves the system performance as a result it reduces the need to increase more heat transfer surface area required to evaporate the juice. The variation of the required total heat transfer surface area with pressure in the last effect is presented in Figure 12 where different bleeding configurations are compared.

Figure 12(a) shows that, an increase in pressure in the last effect necessitates an increase in the required total heat transfer surface area in the five-effect evaporator system. It also shows that, incorporation of bleeding in the system reduces the total heat transfer surface area requirements. A bleeding configuration combination of E1&E3 reduces the required total heat transfer surface area the most as compared to other configurations. The configuration bleed E3 and E4gives similar results while bleed E1and a combination of E2&E4gives similar results. Furthermore, in Figure 12 (a), graphs start from very close points and widen as the scale increases meaning appreciable effects of bleeding is much seen in larger scales of pressure in the last effect. Therefore, the bleeding configuration combination of E1&E3 leads to improved system performance compared to other configurations.



(a) (b)

Figure 12. Variation of (a) total heat transfer surface area, and (b) steam economy with pressure in the last effect at various vapor bleeding configurations

e) Effect of pressure in the last effect on steam economy for different bleeding configurations

Steam economy is the number of kilograms of water vaporized from all the effects per kilogram of steam use (Chantasiriwan, 2017). Pressure in the last effect is related to the steam requirement of the system, as discussed above. An increase in pressure in the last effect increases steam requirement of the system as the system is trying to compensate for the lost overall temperature difference driving force. Also, an increase in steam requirement, decreases steam economy of the system. The variation of steam economy with pressure in the last effect is presented in Figure 12 (b) where different bleeding configurations are compared. Increasing pressure in the last effect decreases the steam economy of the system as shown in Figure 12 (b). With incorporation of vapor bleeding, steam economy of the system is restored and improved more. Again, simulation results show that, bleeding by a combination of E1&E3gives the highest steam economy in the system as compared to other bleeding configurations. Furthermore, bleed E3 and bleed E4show similar results of steam economy in the system. Similarly, bleed E1 and a combination of E2&E4 give same results.

Therefore, for the five-effect evaporator system, with a concern to improve its performance, vapor bleeding is the method to use as it reduces steam consumption and improves steam economy of the system as shown in Figure 12(b). With a well selected and implemented bleeding configuration such as combination of E_1&E_3 the system performance is highly improved than using other configurations.

3.9. Vapor bleeding configuration combination of E_1 and E_3 in the five-effect evaporator

Considering evaporation as one of the energy intensive units in the industry, and as discussed above, vapor bleeding is the one among the methods which is used to improve the MEE system performance as it allows proper energy utilization. Of all the bleeding configurations analyzed in the model, the bleeding configuration combination of E1&E3 is the one that provides the MEE system with the highest performance. With this configuration, the total heat transfer surface area and steam requirements are highly reduced resulting to an improvement of the steam economy of the system. A good design and configuration of vapor bleeding such as E1&E3 allows proper utilization of energy such that even in expansion of the plant (increase in plant scale or capacity) it reduces sharp increase in steam consumption during operation.

4. Conclusions

Based on results obtained through simulation of the present model, several noteworthy conclusions can be drawn.

1. Incorporation of vapor bleeding in the MEE system reduces steam consumption and improves steam economy but at the added cost of the heat exchangers which need to be installed to carry out the bleeding operation.
2. In the five-effect evaporator system with incorporation of sensible heat and heat loss, steam consumption decreaseby 23.73%, while steam economy increase improved by 31.28%when comparing without and with vapor bleeding.
3. Among the six configurations used, a combination of E1&E3 required lowest amount of steam to evaporate the juice to the required syrup, since bled vapors from E_1&E_3 contributes the most in raising feed temperature to its boiling point compared to other configurations. This lowers sensible heat required to raise the feed temperature to its boiling point thus reduces steam consumption and improves steam economy of the system.
4. Bleeding configuration with a combination of E1&E3 has a stronger effect on lowering A_t than bleeding of individual effects or E2&E4 combination. Moreover, increasing percent bleeding decreases the total utilized heat in the system meaning that as

you increase feed pre-heating with the increased bled vapors, the system will not require very high amount of heat in order to evaporate the sugar juice to syrup as sensible heat in raising feed juice temperature to its boiling point has been largely reduced by feed pre-heating using bled vapors. This will result in reduction in steam consumption, improvement in steam economy as well as improvement of process performance as a whole.

5. Increase in percent vapor bleeding increases the mass flow rate of liquor with the bleeding configurations of a combination of E1&E3 performing higher in increasing the mass flow rate of liquor than other configurations. However, an increase in percent bleeding decreases percent solids of liquor in effects. Thus, bleeding has a disadvantage of dilution of syrup, that is, lowers solids concentration, X_{Bi}. Hence, as bleeding improves energy efficiency in the evaporator system, it should be done in a balanced way that the system remains with enough vapor to heat the subsequent effects in the station.

5. Nomenclature

SC	Steam consumption	kg steam/kg water evaporated
A_i	Heat transfer surface area in effects, i	m^2
A_t	Total heat transfer surface area in all 5 effects	m^2
S	Mass flowrate of steam	kg/h
F	Mass flowrate of feed	kg/h
V_i	Mass flowrate of evaporated water from effects i	kg/h
V_{bi}	Mass flowrate of bled vapors from effects i	kg/h
X_{Bi}	Percent solids of liquor in effects, i	%
L	Liquids	kg/h
B_i	Mass flowrate of concentrated liquids (liquor)	kg/h
X_f	Percent solids in the feed	%
P_S, P_{Vi}	Steam pressure, evaporating pressure in effects	kPa
U_i	Overall heat transfer coefficient	J/m^2s^oC
H_f, H_S, H_{Vi}, H_{Bi}	Specific enthalpies (from steam tables) of feed, steam, vapor, and liquor respectively	kJ/kg
T_f	Feed temperature	°C
T_{f1}, T_{f2}	Feed temperature before and after pre-heating using bled vapors	°C
T_S	Steam Temperature	°C
T_{bi}	Evaporating temperatures in effects, i	°C
T_{Bi}	Liquor Temperature in effect i	°C
ΔT_i	Temperature drop in effects, i	°C
C_{pf}	Specific heat capacity of clear sugar juice	kJ/kg°C
Q_i	Rate of heat transfer	J/s
Q_t; Q_L; Q_{sh}; Q_{loss}	Total heat; Latent heat of vaporization; Sensible heat and heat loss respectively	kJ/s
E	Percent heat loss which is assumed to be 5%	%
$S.E$	Steam economy	kg vaporized/ kg steam

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