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Optimization of Heat Transfer Area and Steam Requirement in Multiple Effects Evaporator for Concentration of Juice in Sugar Factory

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ABSTRACT. In maintaining the existence of sugar factories that are still actively operating in Indonesia, efforts should be made to intensify sugar production and/or extensify sugarcane plantations. In terms of the intensification of the process, it is necessary to periodically evaluate the performance of process equipment, especially those that require utilities so that the process is effective and efficient. The process of making sugar passes through six stages, namely: milling, purification, evaporation, cooking, screening, and packaging as the final stage. The evaporation process is a crucial process that determines the success of the entire process because the sugar solution is concentrated from 11% to 64%. The evaporator was designed to use a multiple-effect evaporator to increase the value of steam economy. The objective of this research was to optimize the process condition that requires a minimum total cost at PT. XYZ, a sugar factory. Sugar solution /juice concentration at feed, temperature of feed, and number of effects were variables studied in this research. To achieve this goal, it was necessary to survey the sugar factory to obtain the necessary data. Furthermore, a mathematical model was compiled based on the principle of mass and heat balance and then an Excel-Goal Seek program was used to carry out an accurate optimization. To conclude, for a mass flow rate of 125,000 kg/h with a concentration of 11% sugar solution and a feed temperature of 100^{o}C, the optimum conditions were obtained by employing a quadruple effect evaporator with a minimum annual production cost of IDR 22,090,361,779.00 at PT. XYZ. The optimum conditions obtained were as follows: total evaporator area = 2,443.81 m^2, steam economy = 3.98, and steam demand = 26,028.2 kg/h. A quadruple effect evaporator is commonly utilized in sugar factories in Indonesia.

1. INTRODUCTION

Sugar is one of the plantation commodities that is included in the nine staple foods. In 2019, sugar consumption in Indonesia reached 3,152,230 tons, which is larger than its production of 2,450,000 tons. The sugar shortage in Indonesia is met by importing sugar from Thailand and India. Some factors causing the decrease in sugar production include low efficiency at the farm level and inefficient sugar factories, one of which is the use of outdated sugarcane milling machines, resulting in suboptimal sugar production [1]. The current domestic sugar production is inadequate to meet the domestic demand, and the operational sugar factories are already outdated. Consequently, maintaining the current sugar factories and constructing new ones are required to increase domestic sugar production. The efficiency of the currently operating sugar factories must be increased by intensification and extensification to ensure their existence. In particular, the intensification of the sugar factory processes, including production process intensification, necessitates periodic evaluations of the performance of process equipment that require utilities to ensure an effective and efficient operation. The sugar manufacturer at PG Kedawoeng, Pasuruan, involves six stages: milling, purification, evaporation, cooking, centrifugation, and packaging, which is the final stage [2]. Among the six stages, the evaporation process is the dominant process controlling the success of the entire process, as the process concentrates the juice from a concentration of around 11% to around 64%.

The evaporation process requires a considerable amount of steam as a utility. Therefore, selecting the type of evaporator and designing the evaporation system is crucial to ensure an effective and efficient evaporation process. The evaporator used in this study was designed to use a multiple-effect evaporator with a forward-feed method. The use of a multiple-effect evaporator aimed to increase steam economy, and the application of the forward-feed method aims to reduce the pumping energy of the juice. Based on this background, this journal aims to discuss the optimization of the heat transfer area and steam requirements that give a minimum total of steam and evaporator operation costs in line with the sugar factory's juice production capacity. The research data required includes the composition of the juice entering and leaving the evaporator, the boiling point rise for each effect, the juice production capacity, the steam conditions used (temperature and pressure), and the vacuum system used. The required data are obtained from field surveys in several sugar factories, particularly in East Java, Indonesia.

1.1. Single Effect Evaporation Principle

The single-effect evaporator is depicted in the following diagram:

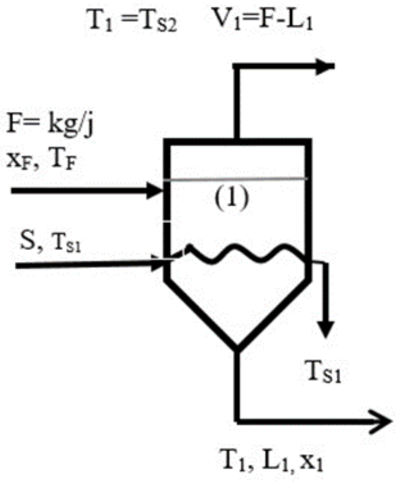

Figure 1. Single effect evaporator (Redrawn from [3])

Based on Figure 1, the steam (S) condenses outside the evaporator as condensate or dew droplets. The sugar solution inside the evaporator has the same concentration and temperature, T_1, which is the boiling point of the solution. The temperature of the incoming steam, T_{S1}, is also equal to T_1 since the steam is in equilibrium with the boiling point of the solution. If the evaporated solution is assumed to be diluted and the solvent is water, then 1 kg of incoming steam will evaporate around 1 kg of water from the solution as it acts as a heating agent. This applies if the incoming feed, T_F, approaches its boiling point. The concept of the overall heat transfer coefficient is used in calculating the rate of heat transfer inside the evaporator. The rate of heat transfer is expressed in Equation (1) as follows:

$$q = UA\Delta T = UA(T_S - T_1) \tag{1}$$

where: q = heat transfer rate, W; U = overall heat transfer coefficient, W/m^2.K; A = heat transfer area of the evaporator, m^2; T_{S1} = temperature of the condensing steam, K; T_1 = boiling point temperature of the solution, K. The overall heat transfer coefficient U can be estimated using the approach:

$$\frac{1}{U} = \frac{1}{h_{io}} + \frac{1}{h_o} \tag{2}$$

with: h_{io} = convective heat transfer coefficient of condensing steam and h_o = convective heat transfer coefficient of the juice solution calculated based on the boiling point of the solution.

1.2. Calculations for multi-effect evaporators

Multiple effect evaporators are depicted in detail in the following figure:

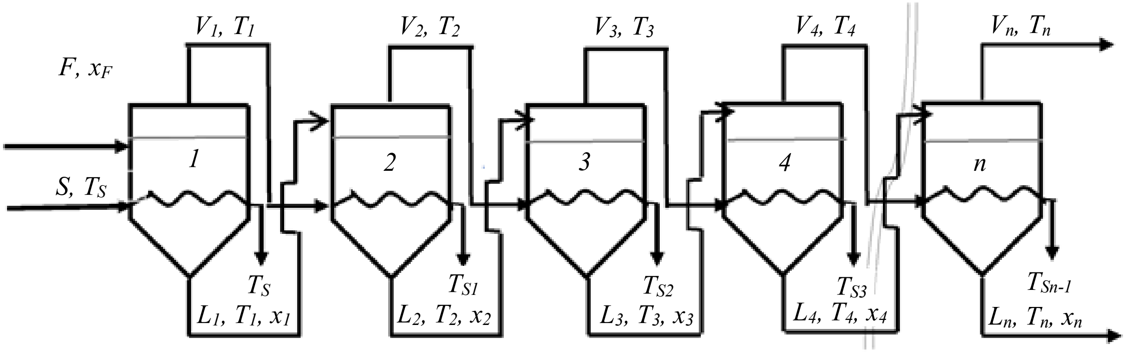

Figure 2. Multiple effect evaporator with number of effects n forward feed type

In a multiple-effect evaporator, the implications of each kilogram of water evaporated are twofold: the amount of steam consumed is inversely proportional to the number of effects used, and the amount of cooling water used in the condenser is inversely proportional to the number of effects. In order for heat transfer to occur effectively, a temperature drop must occur for each effect. In other words, the steam temperature produced in a particular effect must be higher than the boiling point temperature of the solution in the next effect, or it can be expressed in inequality 3 with temperature (T) and pressure (P) symbols as follows:

$$T_1 > T_2 > \ldots\ldots > T_n, \text{ likewise: } P_1 > P_2 > \ldots\ldots\ldots > P_n \tag{3}$$

with: $T_1, T_2, \ldots\ldots\ldots T_n$ is the temperature of the water vapor outward from the 1st, 2nd, … until n number of effect; whilst $P_1, P_2, \ldots\ldots\ldots P_n$ is the outward pressure of water vapor from the 1st, 2nd, … until n number of effect. Based on the given data, calculations for a multiple-effect evaporator system require the values of heat transfer area in each effect (A_n), the mass (kg) of steam per hour to be supplied (S), and the amount of steam leaving each effect (S_n). The following data is usually available or known: (1) the vapor pressure in the first effect, (2) the vapor pressure in the last effect, (3) the feed conditions (concentration of the solution and temperature) and the mass flow rate of the feed entering the first effect, (4) the final concentration in the liquid leaving the last effect, (5) physical properties such as enthalpy and/or heat capacity of the liquid and vapor, and (6) the overall heat transfer coefficient in each effect (Un). Based on Figure 2 above, the following equations can be used: total mass balance, component mass balance for the solution, and heat balance for each effect from 1 to 7 as described below.

Total and component of the material balance for the first effect

$$F = L_1 + V_1 \tag{4}$$

$$Fx_F = L_1 x_1 \tag{5}$$

$$Fh_F + S\lambda_{S1} = L_1 h_1 + V_1 H_1 \tag{6}$$

$$Fc_{pF}T_F + S\lambda_{S1} = L_1 c_{p1} T_1 + (F - L_1)H_1 \tag{7}$$

or

$$S = \frac{L_1 c_{p1} T_1 + (H_1 - c_{pF}T_F)F - L_1 H_1}{S\lambda_{S1}} \tag{8}$$

With: F = feed mass flow rate, kg/h; L_1 = output mass flow rate of concentrated solution, kg/h; V_1 = output mass flow rate of vapor, kg/h; S = incoming mass flow rate of steam, kg/h; cp_F and cp_1 are specific heat capacities of feed and concentrated solution, kJ/kg.K, λ_{S1}= latent heat of vaporization, kJ/kg, x_F and x_1 are concentrations of solution in feed and leaving concentrated solution, mass percent, T_F and T_1 are temperatures of feed and leaving concentrated solution, °C, H_1 = enthalpy of saturated vapor leaving, kJ/kg. Equation (8) can be used to calculate the amount of steam required (S). The heat capacity of concentrated solution is influenced by the concentration of solution and is expressed by the following equation [4]:

$$C_p = 14{,}275 - 6{,}6.10^{-2}(T + 273) + 1{,}1.10^{-4}(T + 273)^2 - 2{,}7.10^{-2}x \tag{9}$$

With: Cp = heat capacity of the juice, J/g.K, T = temperature of the juice, °C, x = juice concentration, mass fraction. Another simpler correlation in which the heat capacity is only influenced by the syrup concentration is provided by Geankoplis et al. [3] as follows:

$$C_p = 4{,}39 - 2{,}35x \tag{10}$$

With: C_p = heat capacity of juice, kJ/kg.K.

The enthalpy of saturated steam is estimated from the saturated steam enthalpy data plus the specific heat capacity of steam multiplied by the Boiler Pressure Ratio (BPR) value as follows:

$$H_i = H_{Si+1} + 1{,}884BPR_i \tag{11}$$

and the saturated steam enthalpy, H_S, saturated water enthalpy, h_S, and steam latent heat of evaporation, λ_S, are calculated based on empirical equations regressed from thermodynamic properties data of saturated steam and saturated water as follows [5]:

$$H_s = -0{,}0023T^2 + 2{,}0246T + 2496{,}5 \tag{12}$$

$$h_s = 4{,}2071T - 1{,}4304 \tag{13}$$

$$\lambda_S = H_S - h_S \tag{14}$$

For the total mass balance, juice mass balance, and heat balance for each effect-other effects, they are described as follow.

Total and component of the material balance for the second effect

$$L_1 = L_2 + V_2 \tag{15}$$

$$L_1x_1 = L_2x_2 \tag{16}$$

$$L_1h_1 + V_1\lambda_{S2} = L_2h_2 + V_2H_2 \tag{17}$$

$$L_1c_{p1}T_1 + (F - L_1)\lambda_{S2} = L_2c_{p2}T_2 + (L_1 - L_2)H_2 \tag{18}$$

or it can be rewritten into the following

$$(H_2 + \lambda_{S2} - c_{p1}T_1)L_1 + (c_{p2}T_2 - H_2)L_2 = F\lambda_{S2} \tag{19}$$

Total and component of the material balance for the third effect

$$L_2 = L_3 + V_3 \tag{20}$$

$$L_2x_2 = L_3x_3 \tag{21}$$

$$L_2h_2 + V_2\lambda_{S3} = L_3h_3 + V_3H_3 \tag{22}$$

$$L_2c_{p2}T_2 + V_2\lambda_{S3} = L_3c_{p3}T_3 + (L_2 - L_3)H_3 \tag{23}$$

$$L_2c_{p2}T_2 + (L_1 - L_2)\lambda_{S3} = L_3c_{p3}T_3 + (L_1 - L_2)H_3 \tag{24}$$

or it can be rewritten into the following

$$\lambda_{S3}L_1 + (c_{p2}T_2 - \lambda_{S3} - H_3)L_2 + (H_3 - c_{p3}T_3)L_3 = 0 \tag{25}$$

$$\lambda_{S3}L_1 + (c_{p2}T_2 - \lambda_{S3} - H_3)L_2 = (c_{p3}T_3 - H_3)L_3 \tag{26}$$

Total and component of the material balance for the fourth effect

$$L_3 = L_4 + V_4 \tag{27}$$

$$L_3x_3 = L_4x_4 \tag{28}$$

$$L_3h_3 + V_3\lambda_{S4} = L_4h_4 + V_4H_4 \tag{29}$$

$$L_3c_{p3}T_3 + (L_2 - L_3)\lambda_{S4} = L_4c_{p4}T_4 + (L_3 - L_4)H_4 \tag{30}$$

or it can be rewritten into the following

$$\lambda_{S4}L_2 + (c_{p3}T_3 - \lambda_{S4} - H_4)L_3 + (H_4 - c_{p4}T_4)L_4 = 0 \tag{31}$$

$$\lambda_{S4}L_2 + (c_{p3}T_3 - \lambda_{S4} - H_4)L_3 = (c_{p4}T_4 - H_4)L_4 \tag{32}$$

Total and component of the material balance for the fifth effect

$$L_4 = L_5 + V_5 \tag{33}$$

$$L_4x_4 = L_5x_5 \tag{34}$$

$$L_4h_4 + V_4\lambda_{S5} = L_5h_5 + V_5H_5 \tag{35}$$

$$L_4c_{p4}T_4 + (L_3 - L_4)\lambda_{S5} = L_5c_{p5}T_5 + (L_4 - L_5)H_5 \tag{36}$$

or it can be rewritten into the following

$$\lambda_{S5}L_3 + (c_{p4}T_4 - \lambda_{S5} - H_5)L_4 + (H_5 - c_{p5}T_5)L_5 = 0 \tag{37}$$

$$\lambda_{S5}L_3 + (c_{p4}T_4 - \lambda_{S5} - H_5)L_4 = (c_{p5}T_5 - H_5)L_5 \tag{38}$$

Total and component of the material balance for the sixth effect

$$L_5 = L_6 + V_6 \tag{39}$$

$$L_5x_5 = L_6x_6 \tag{40}$$

$$L_5h_5 + V_5\lambda_{S6} = L_6h_6 + V_6H_6 \tag{41}$$

$$L_5c_{p5}T_5 + (L_4 - L_5)\lambda_{S6} = L_6c_{p6}T_6 + (L_5 - L_6)H_6 \tag{42}$$

or it can be rewritten into the following

$$\lambda_{S6}L_4 + (c_{p5}T_5 - \lambda_{S6} - H_6)L_5 + (H_6 - c_{p_6}T_6)L_6 = 0 \tag{43}$$

$$\lambda_{S6}L_4 + (c_{p5}T_5 - \lambda_{S6} - H_6)L_5 = (c_{p_6}T_6 - H_6)L_6 \tag{44}$$

Total and component of the material balance for the seventh effect

$$L_6 = L_7 + V_7 \tag{45}$$

$$L_6x_6 = L_7x_7 \tag{46}$$

$$L_6h_6 + V_6\lambda_{S7} = L_7h_7 + V_7H_7 \tag{47}$$

$$L_6c_{p6}T_6 + (L_5 - L_6)\lambda_{S7} = L_7c_{p7}T_7 + (L_6 - L_7)H_7 \tag{48}$$

or it can be rewritten into the following

$$\lambda_{S7}L_5 + (c_{p6}T_6 - \lambda_{S7} - H_7)L_6 = (c_{p_7}T_7 - H_7)L_7 \tag{49}$$

In general can be written equations:

$$\lambda_{Si}L_{i-2} + (c_{pi-1}T_{i-1} - \lambda_{Si} - H_i)L_{i-1} = (c_{p_i}T_i - H_i)L_i \tag{50}$$

with i = effect number.

From Equation (50) of mass and heat balance, a set of equations can be derived to calculate the outlet flow rates of the juice from each effect, other than the inlet and outlet juice flow rates of the last effect, since the outlet flow rate of juice from the last effect can be calculated from the total mass balance and the concentration of the juice first. For a triple effect evaporator, Equation (51) and (52) can then be formulated:

$$(H_2 - \lambda_{S2} - c_{p1}T_1)L_1 + (c_{p2}T_2 - H_2)L_2 = F\lambda_{S2} \tag{51}$$

$$\lambda_{S3}L_1 + (c_{p2}T_2 - \lambda_{S3} - H_3)L_2 = (c_{p3}T_3 - H_3)L_3 \tag{52}$$

Value of $F, L_3, c_{p1}, c_{p2,}, c_{p3}, H_2, H_3, T_1, T_2, T_3, \lambda_{S_2}$ and λ_{S3} from both equations, it is known or can be calculated beforehand, so both equations are two simultaneous linear algebraic equations with two variables, which is L_1 and L_2, which can be solved by Gauss-Jordan elimination or other methods. Using similar analysis, equations can be derived for other multiple effect evaporators.

For a quadruple effect evaporator, three equations can be formulated as follows:

$$(H_2 - \lambda_{S2} - c_{p1}T_1)L_1 + (c_{p2}T_2 - H_2)L_2 = F\lambda_{S2} \tag{53}$$

$$\lambda_{S3}L_1 + (c_{p2}T_2 - \lambda_{S3} - H_3)L_2 + (H_3 - c_{p3}T_3)L_3 = 0 \tag{54}$$

$$\lambda_{S4}L_2 + (c_{p3}T_3 - \lambda_{S4} - H_4)L_3 = (c_{p4}T_4 - H_4)L_4 \tag{55}$$

Value of $L_4, c_{p1}, c_{p2}, c_{p3}, c_{p4}, H_2, H_3, H_4, T_1, T_2, T_3, T_4, \lambda_{S2}, \lambda_{S3}$ and λ_{S4} from these three equations, which are already known or can be calculated beforehand, they form a set of 3 simultaneous linear algebraic equations with 3 variables, namely L_1, L_2, and L_3, which can be solved by Gaussian elimination or other methods.

For a 5-effect evaporator or quintuple effect evaporator, 4 equations can be formulated as follows:

$$(H_2 - \lambda_{S2} - c_{p1}T_1)L_1 + (c_{p2}T_2 - H_2)L_2 = F\lambda_{S2} \tag{56}$$

$$\lambda_{S3}L_1 + (c_{p2}T_2 - \lambda_{S3} - H_3)L_2 + (H_3 - c_{p3}T_3)L_3 = 0 \tag{57}$$

$$\lambda_{S4}L_2 + (c_{p3}T_3 - \lambda_{S4} - H_4)L_3 + (H_4 - c_{p4}T_4)L_4 = 0 \tag{58}$$

$$\lambda_{S5}L_3 + (c_{p4}T_4 - \lambda_{S5} - H_5)L_4 = (c_{p5}T_5 - H_5)L_5 \tag{59}$$

Value of $L_5, c_{p1}, c_{p2}, c_{p3}, c_{p4}, c_{p5}, H_2, H_3, H_4, T_1, T_2, T_3, T_4, \lambda_{S2}, \lambda_{S3}, \lambda_{S4},$ and λ_{S5} from the four equations, it is already known or can be calculated beforehand, thus the four equations represent a system of 4 simultaneous linear equations with 4 variables namely L_1, L_2, L_3, and L_4 which can be solved by Gauss-Jordan elimination or other methods.

For a 6-effect evaporator or sextuple effect evaporator, a set of 5 equations can be formulated as follows:

$$(H_2 - \lambda_{S2} - c_{p1}T_1)L_1 + (c_{p2}T_2 - H_2)L_2 = F\lambda_{S2} \tag{60}$$

$$\lambda_{S3}L_1 + (c_{p2}T_2 - \lambda_{S3} - H_3)L_2 + (H_3 - c_{p3}T_3)L_3 = 0 \tag{61}$$

$$\lambda_{S4}L_2 + (c_{p3}T_3 - \lambda_{S4} - H_4)L_3 + (H_4 - c_{p4}T_4)L_4 = 0 \tag{62}$$

$$\lambda_{S5}L_3 + (c_{p4}T_4 - \lambda_{S5} - H_5)L_4 + (H_5 - c_{p5}T_5)L_5 = 0 \tag{63}$$

$$\lambda_{S6}L_4 + (c_{p5}T_5 - \lambda_{S6} - H_6)L_5 = (c_{p6}T_6 - H_6)L_6 \tag{64}$$

Value of $L_6, c_{p1}, c_{p2}, c_{p3}, c_{p4}, c_{p5}, c_{p6}, H_2, H_3, H_4, H_5, H_6, T_1, T_2, T_3, T_4, T_5, T_6, \lambda_{S2}, \lambda_{S3}, \lambda_{S4}, \lambda_{S5}$ and λ_{S6} from the five equations above, it is known or can be calculated beforehand that these equations are 5 simultaneous linear algebraic equations with 5 variables, namely L_1, L_2, L_3, L_4, and L_5, which can be solved by Gaussian elimination or other methods.

Furthermore, for a 7-effect evaporator or heptuple effect evaporator, 6 equations can be formulated as follows:

$$(H_2 - \lambda_{S2} - c_{p1}T_1)L_1 + (c_{p2}T_2 - H_2)L_2 = F\lambda_{S2} \tag{65}$$

$$\lambda_{S3}L_1 + (c_{p2}T_2 - \lambda_{S3} - H_3)L_2 + (H_3 - c_{p3}T_3)L_3 = 0 \tag{66}$$

$$\lambda_{S4}L_2 + (c_{p3}T_3 - \lambda_{S4} - H_4)L_3 + (H_4 - c_{p4}T_4)L_4 = 0 \tag{67}$$

$$\lambda_{S5}L_3 + (c_{p4}T_4 - \lambda_{S5} - H_5)L_4 + (H_5 - c_{p5}T_5)L_5 = 0 \tag{68}$$

$$\lambda_{S6}L_4 + (c_{p5}T_5 - \lambda_{S6} - H_6)L_5 + (H_6 - c_{p6}T_6)L_6 = 0 \tag{69}$$

$$\lambda_{S7}L_5 + (c_{p6}T_6 - \lambda_{S7} - H_7)L_6 = (c_{p7}T_7 - H_7)L_7 = 0 \tag{70}$$

Value of $L_6, c_{p1}, c_{p2}, c_{p3}, c_{p4}, c_{p5}, c_{p6}, c_{p7}, H_2, H_3, H_4, H_5, H_6, H_7, T_1, T_2, T_3, T_4, T_5, T_6, T_7, \lambda_{S2}, \lambda_{S3}, \lambda_{S4}, \lambda_{S5}, \lambda_{S6}$ and λ_{S7} from the six equations are already known or can be calculated beforehand, these six equations constitute a system of 6 simultaneous linear algebraic equations with 6 variables, namely L_1, L_2, L_3, L_4, L_5, and L_6, which can be solved using Gauss-Jordan elimination or other methods. Once the flow rates of each effect, L_1, L_2, L_3, L_4, L_5, and L_6, are calculated, the rates of water vapor leaving each effect, V_1, V_2, V_3, V_4, V_5, V_6, and V_7, can then be determined. The heat transfer area in each effect is assumed to be the same. In a multiple effect evaporator, the juice must be concentrated to a suitable concentration for crystallization, which is typically around 60% by mass. Steam used as heating medium in the multiple effect evaporator can be generated from low-pressure steam waste from a turbine. [6].

2. MATERIALS AND METHODS

2.1 Data of fixed variables used for simulation

The following data were obtained from PT. XYZ sugar factory. The flow rate of sugar solution collected from several sugar factories, especially in East Java area, Indonesia, was approximately 125,000 kg/hour. The concentration of sugar in the concentrated sugar solution produced from the last effect was approximately 64% mass. Water vapor pressure at the last effect was known to be 15.53 kPa with temperature of 54.66°C. The temperature of the steam on the first effects was 117°C.

2.2 Variables observed:

Diluted feed of sugar solution temperatures were in the range of 60°C to 100°C with 10°C intervals. The concentration of dilute solution ranged from 7% to 15% with an interval of 2%. 3. The number of effects were varied from 3 to 7.

2.3 Optimization of Heat Transfer Area in Multi-Effect Evaporator

The calculation for optimization purposes is solved through a trial-and-error method with the following seven steps as follows [4]:

1. Based on the known concentration of the juice leaving the last effect and the vapor pressure entering the last effect, the boiling point in the last effect can be determined through overall mass balance and component mass balance calculations to obtain L_1, L_2, ..., and L_n, V_1, V_2, ..., and V_n. The steam requirement (S) for the first effect can also be calculated.

2. The amount of heat transferred per hour in the first effect of the evaporator with forward feed in Figure 2 can be calculated as:

$$q_1 = U_1 A_1 \Delta T_1 \tag{71}$$

with ΔT_1 is the difference between the steam condensation temperature and the boiling point of the juice (T_s - T_1). Assuming that the juice solution does not experience boiling point elevation, neglecting the heat of dissolution, ignoring the sensible heat required to heat the feed to its boiling point, and assuming partial evaporation of water, the amount of heat released in the form of steam can be calculated. This steam then condenses in the second effect, releasing a heat q_2, and for the n effect, it can be expressed by the following equation:

$$q_2 = U_2 A_2 \Delta T_2 \tag{72}$$

$$q_n = U_n A_n \Delta T_n \tag{73}$$

By analogy, the values of q_n can also be developed. In the design and to facilitate the fabrication of the evaporator, the heat transfer area of each effect is considered the same and assuming that the heat transfer rate in each effect is the same, the equations can be written as follows:

$$q_1 = q_2 = \cdots = q_n = q \tag{74}$$

$$U_1 A_1 \Delta T_1 = U_2 A_2 \Delta T_2 = \cdots = U_n A_n \Delta T_n = UA\Delta T \tag{75}$$

$$A_1 = A_2 = \cdots = A_n = A \quad (76)$$

Consequently:

$$\frac{q}{A} = U_1 A_1 = U_2 A_2 = \cdots = U_n \Delta T_n \quad (77)$$

q/A is the heat transfer flux that is for the maximum organic solution around 12.000 Btu/hour.ft^2 [8].

3. The temperature difference (ΔT) in several evaporator effects is approximately inversely proportional to the values of U. Therefore, since ΔT_1 is proportional to $1/U_1$, then:

$$\Delta T_1 = \sum \Delta T \frac{\frac{1}{U_1}}{\frac{1}{U_1} + \frac{1}{U_2} + \cdots \frac{1}{U_n}} \quad (78)$$

Similar equations can be written for ΔT_2, ΔT_3, ... and ΔT_n, where U_1 is the heat transfer coefficient for the first effect, W/m^{2}K, U_2 is the heat transfer coefficient for the second effect, W/m^{2}K, U_3 is the heat transfer coefficient for the third effect, W/m^{2}K, and Un is the heat transfer coefficient for the nth effect, W/m^{2}K. The overall heat transfer coefficient value is influenced by the concentration of the juice. Using a quintuple effect evaporator, Storia (2019) investigated the effect of juice concentration on the overall heat transfer coefficient and reported that as the juice concentration increased from 18 ºBrix in the first effect to 68 ºBrix in the fifth effect, and using the Dessin method, the overall heat transfer coefficient value would decrease from 3.46 kW/m^2.K in the first effect to 0.86 kW/m^2.K in the fifth effect [9].

Furthermore, the overall heat transfer coefficient U value, particularly for vertical tube evaporators, can be determined using empirical equations developed based on the relationship between boiling temperature and U value [10]. The original data is in the form of a graph showing the relationship between temperature and overall heat transfer coefficient in British units, which was then converted to metric units and regressed by the author to obtain the following empirical equation:

$$U = 0{,}645 T^{1{,}8129} \quad (79)$$

with U = overall heat transfer coefficient, W/m^2.K, T = boiling temperature of the sugar solution, K. Any effect that has an extra heating load will require a proportionally larger ΔT. Prediction of the overall heat transfer coefficient involving three variables namely: sugar solution concentration, x, sugar solution temperature, T_f and feed flow rate, F, especially for Robert type evaporator is given by Srivastava (2013) with the following empirical equation [11]:

$$\frac{U}{U_{maks}} = 0{,}1909 \left(\frac{x}{x_{maks}}\right)^{-3{,}153} \left(\frac{T_f}{T_{maks}}\right)^{-0{,}298} \left(\frac{F}{F_{maks}}\right)^{0{,}0615} \quad (80)$$

With: U_{maks} = 5,71 kW/m^2.°C; x_{max} = 0,57; T_{max} = 122°C dan F_{max} = 100 kg/s.

The value of $\Sigma\Delta T$ is calculated based on the increase in the boiling point of the juice in each effect, as follows:

$$\sum \Delta T = \Delta T_1 + \Delta T_2 + \cdots \Delta T_n = T_{SF} - T_n - [BPR_1 + BPR_2 + \cdots + BPR_n] \quad (81)$$

With $\Delta T_1 = (T_S - T_1)$, the temperature difference available for the first effect, ΔT2 = (TS1 - T2), the temperature difference available for the second effect, $\Delta T_n = (T_{Sn-1} - T_n)$ = the temperature difference available for the n-th effect, T_1 = the boiling temperature of the syrup in the first effect, K, T_2 = the boiling temperature of the syrup in the second effect, K, T_n = the boiling temperature of the syrup in the n-th effect, K, T_S = the steam inlet temperature to the first effect, K, T_{S1} = the temperature of saturated steam leaving the second effect, K, T_{Sn} = the temperature of saturated steam leaving the n effect, K, BPR_1 = the boiling point rise of syrup in the first effect, BPR_2 = the boiling point rise of syrup in the second effect, and BPR_n = the boiling point rise of syrup in the n effect. The value of BPR is calculated by the following empirical equation [4]:

$$BPR = 1{,}78x + 6{,}22x^2 \quad (82)$$

The equation is as follows, where x represents the mass fraction of the solution [12]:

$$T_f = -227{,}03 + \frac{3.816{,}44}{18{,}3036 - \ln\left[7{,}5\left(p + \frac{\rho g H}{2.000}\right)\right]} + \frac{2x}{100 - x} \quad (83)$$

With: T_f = boiling temperature of the juice, °C; p = vapor pressure inside the effect, kPa; ρ = density of the juice, kg/m^3, g = acceleration due to gravity, m/s^2; H = height of juice in the evaporator, m.

4. By applying mass and heat balance to the first effect, the amount of evaporated water can be calculated and consequently the amount of steam (S) entering the first effect, and the value of heat transferred in each effect (q) can be estimated.

5. By applying the heat transfer rate equation, $q = UA\Delta T$ for every effect, heat transfer area can be calculated: A_1, A_2, ..., and A_n. The arithmetic mean value A_m is calculated using the equation:

$$A_m = \frac{A_1 + A_2 + \cdots + A_n}{n} \tag{84}$$

6. If the values of A_1, A_2, A_3, ..., and A_n are close enough to each other, then the calculation is considered complete and a second calculation is not needed. However, if conversely, the values of A_1, A_2, A_3, ..., and A_n are almost different, the second calculation should be carried out with the steps mentioned above, then the new values of $\Delta T_1'$, $\Delta T_2'$, ..., and $\Delta T_n'$ are calculated using the following equation:

$$\Delta T_1' = \frac{\Delta T_1 A_1}{A_m} \tag{85}$$

$$\Delta T_2' = \frac{\Delta T_2 A_2}{A_m} \tag{86}$$

$$\Delta T_n' = \frac{\Delta T_n A_n}{A_m} \tag{87}$$

The sum of $\Delta T_1' + \Delta T_2' + \ldots + \Delta T_n'$ should be equal to the original $\Sigma\Delta T$. If it is not, adjust proportionally all the calculated values of $\Delta T'$ based on the boiling point rise in each effect, and as shown before, calculate q_1, q_2,…and q_n and A_1, A_2,…and A_n using the new values of $\Delta T_1' + \Delta T_2' + \ldots + \Delta T_n'$

7. Step 6 is repeated until the value of the steam velocity exiting each effect is equal to a maximum allowable difference tolerance of 10%, and the calculated heat transfer area for each effect is equal.

2.4. Estimated Production Cost of Concentrated Juice

The production cost of concentrated juice consists of two components: steam cost and evaporator cost. The steam requirement can be calculated from the mass and heat balance of the evaporator, and subsequently the steam cost can be calculated using the following equation:

$$BS = SC_S \tag{88}$$

where BS represents the steam cost and C_s represents the steam price. Furthermore, the annual steam cost (BST) is calculated using the following equation:

$$BST = JOT \times JJH \times C_S \tag{89}$$

With: JOT = number of operational days of sugar factory per year and JJH = number of operational hours of sugar factory per day. The operational days of sugar factories in Indonesia range from 150-180 effective days per year, which is derived from the number of days during the sugarcane milling season in several sugar factories [13]. In general, sugar factories start operating from late May or early June until October. The annual evaporator cost can be calculated as follows [14]:

$$CE = 16.595{,}87A^{0{,}54} \tag{90}$$

With A being the heat transfer area of the evaporator in square meters, and CE being the evaporator cost in USD in 2002, adjusted for inflation. The average currency exchange rate in November 2021 from Bank Indonesia was 1 USD = IDR. 14,462.00. The Chemical Engineering Plant Cost Index (CEPCI) values for 2002 and 2021 were 395.6 and 655.9, respectively. The empirical equation was obtained from regression data that took the form of a specific curve, particularly for the evaporator.

$$BET = 0{,}15(1 + 0{,}6)CE \tag{91}$$

where BET represents the annual evaporator cost, CE is the purchase price of the evaporator, and the multiplying factor of 0.15 represents the depreciation cost of the evaporator purchase price, while the multiplying factor of (1 + 0.6) represents the cost of piping installation and the attachment of equipment to the evaporator.

2.5 Optimization of Annual Juice Production Costs

The total annual production cost of concentrated sugarcane juice (BPT) is the sum of the annual steam cost (BST) and the annual evaporator cost (BET), expressed by the following equation:

$$BPT = BST + BET \tag{92}$$

In this study, the annual total production cost of syrup was calculated for each number of effects investigated. By plotting the relationship between the number of effects and the annual total production cost of syrup, the optimum number of effects with the minimum total production cost can be determined [15].

3. RESULTS AND DISCUSSION

3.1. Relationship between the amount of effect on evaporator installation costs, steam costs *and annual total juice production costs*

The relationship between the number of effects and the evaporator installation cost, steam cost, and total annual production cost is shown in the following figure:

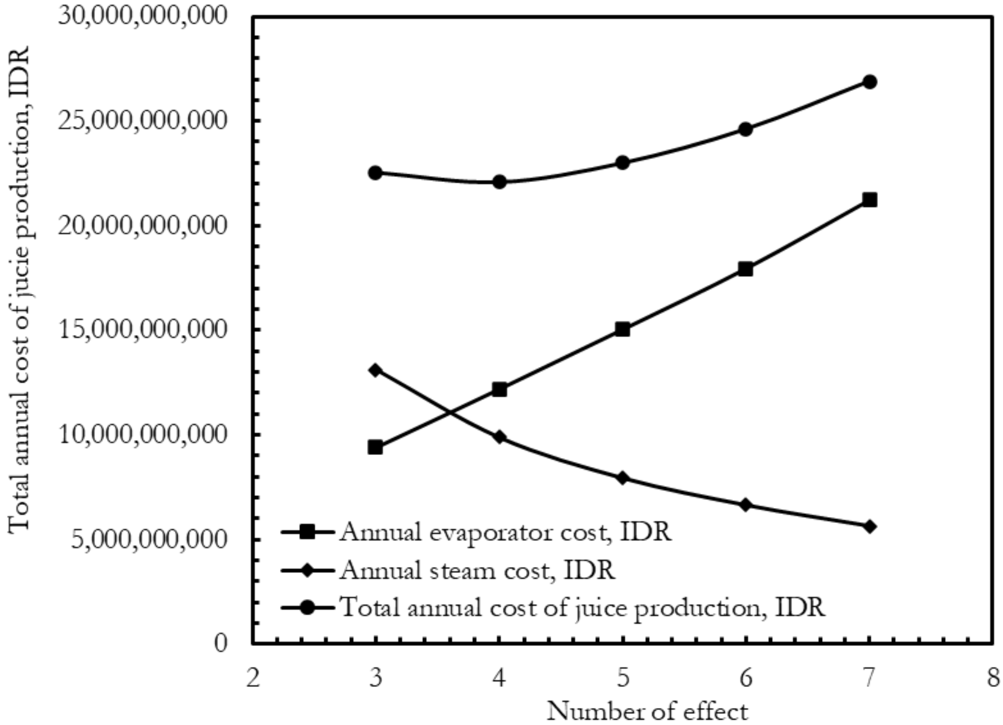

Figure 3. The relationship between the number of effects and the evaporator cost, steam cost, and total annual cost for the production of 125,000 kg/h of syrup

From Figure 3, the annual evaporator cost will increase linearly with the increasing number of effects, with an increase of around 2.5 times. The increase in the number of effects will increase the total heat transfer area requirement, which will in turn increase the cost of producing juice. On the other hand, the annual steam cost will decrease gradually as the number of effects increases. The number of effects will indeed increase the steam economy (SE) from 2.99 to 7.94, but it will also increase the total annual cost of producing juice after it is combined with the annual steam cost. Optimizing the heat transfer area requirement and steam requirement must be based on the minimum total cost of producing juice per year. From Figure 3, the minimum total cost of producing juice per year is achieved at IDR 22,090,361,779.00, which is shown by the evaporator with 4 (four) effects. At that condition, the total evaporator area = 2,443.81 m^2, steam economy = 3.98, and steam requirement = 26,028.2 kg/h. Four effects evaporator is utilized by most of sugar factories in Indonesia.

3.2. Effect of the sum of effects on the annual production cost of juice total for various feed temperatures

The effect of number of effects and feed temperature on the total annual production cost of juice is presented in Figure 4. From Figure 4, as the feed temperature increases from 60°C to 100°C, the total annual production cost of juice will decrease. This is because an increase in juice concentration in the feed will decrease the water content, thus reducing the amount of water evaporated. Furthermore, the steam requirement will also decrease from 43,091 kg/hour to 14,893 kg/hour. As the number of effects increases from 4 to 7, the total cost will increase. This is because an increase in the number of effects will increase the heat transfer area from 1,931 m^2 to 4,433 m^2. Similarly, an increase in the number of effects for various feed temperatures will reduce steam requirements, while an increase in the number of effects will increase the cost of the evaporator equipment by approximately 2.5 times. From Figure 4, the optimum condition that provides the minimum total annual production cost of juice is achieved at a feed temperature of 100°C and 4 effects with a total cost of IDR 22,090,361,779.00 and the influence of the evaporator cost is greater than the steam cost.

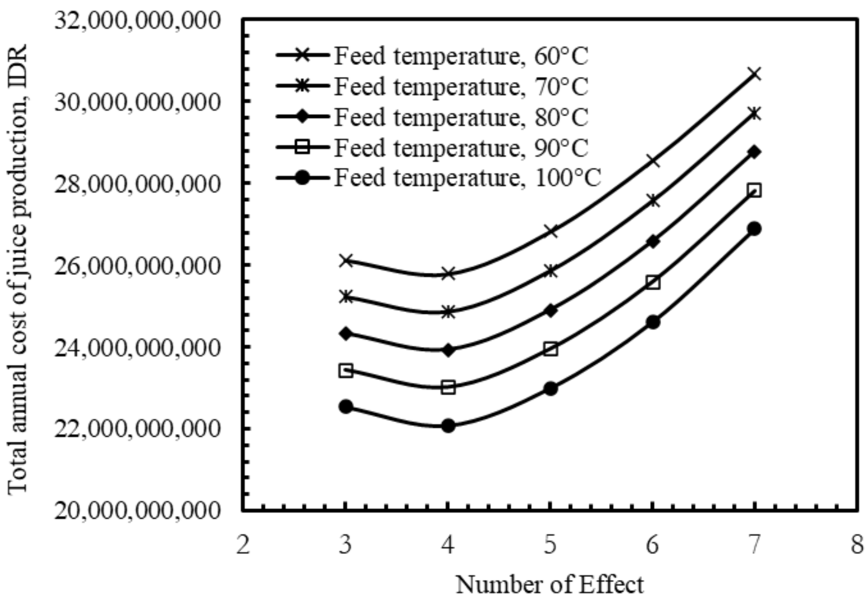

Figure 4. Effect of the number of effects on the annual total juice production cost for various feed temperatures at a feed rate of 125,000 kg/h and a feed concentration of 11%.

3.3. Effect of the sum of effects on the annual total juice *production* cost *for various concentrations of feed juice at a feed temperature of 100 ℃*

The effect of the number of effects and the feed concentration on the total annual juice production costs, particularly at a temperature of 100ºC, is presented in Figure 5. For various numbers of effects, increasing the juice concentration in the feed will lower the juice production costs. This is because higher juice concentration leads to lower water concentration in the juice. As a result, for the same juice product concentration of 64%, increasing the juice concentration in the feed from 7% to 11% will also decrease the amount of water that needs to be evaporated. Consequently, the steam requirement will also decrease. For a four-effect system, the steam requirement will decrease from 28.151 kg/hour at a juice feed concentration of 7% to 23.902 kg/hour at a juice feed concentration of 15%. Moreover, for the same juice feed concentration of 7%, increasing the number of effects will reduce the steam requirement from 37.358 kg/hour at three effects to 37.358 kg/hour at seven effects. Based on the effect of the juice feed concentration, the optimum condition for achieving the minimum total annual juice production cost of IDR.20.822.633.010,00 is with four effects and a juice feed concentration of 15%. The quadruple effect evaporator system is commonly used in various new sugar mills in Indonesia due to its high evaporation efficiency [16].

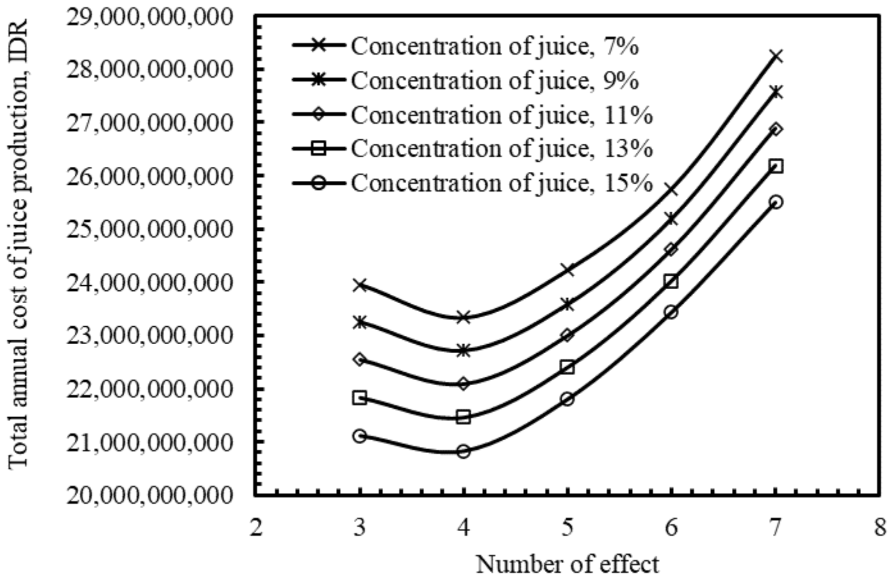

Figure 5. Effect of number of effects on total annual juice production cost for various feed juice concentrations at 100°C feed temperature

3.4. Effect of temperature on annual total juice *production* costs *for various concentrations of juice in feed on quadruple effect evaporators*

From the calculations performed for variations in temperature from 60°C to 100°C and variations in juice concentration in the feed from 7% to 15%, it was found that the optimum condition was always achieved with a four-effect or quadruple effect evaporator system. Simulation was then conducted on the four-effect evaporator system to determine the total annual juice production cost for the variations in temperature and juice concentration in the feed. The results are presented in Figure 6 below:

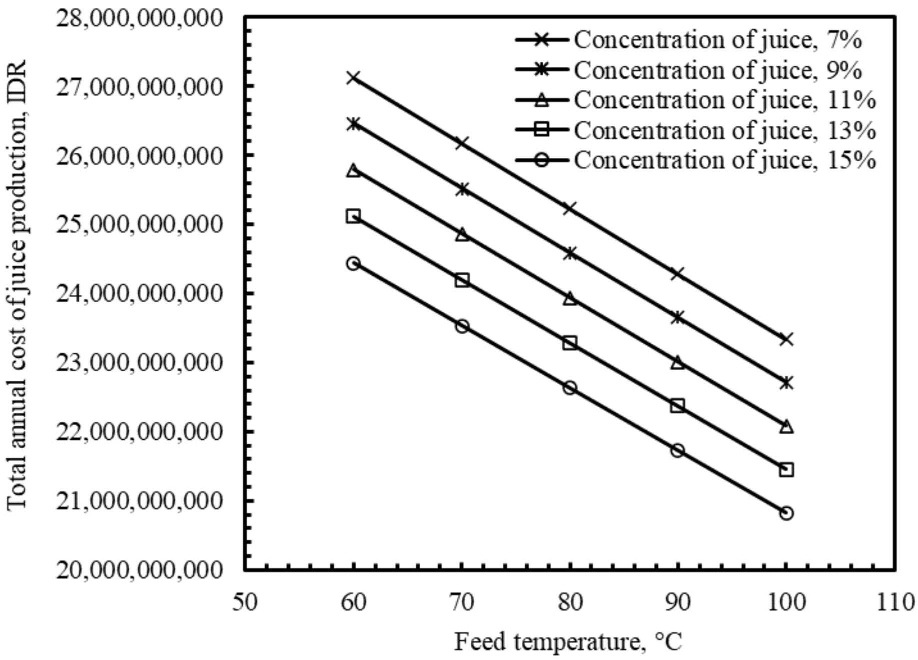

Figure 6. The relationship between feed temperature and the total annual juice production cost for various juice concentrations in the feed in a quadruple effect evaporator system.

From Figure 6, for every concentration of feed, the total annual production cost of sugar solution (juice) will decrease linearly as the temperature of feed increases. The decreasing pattern is the same, in the form of a straight line. For the same feed temperature, the total annual production cost of sugar solution will decrease as the concentration of feed increases. For example, at a feed temperature of 100°C, the total annual production cost of sugar solution will decrease from IDR 23,335,553,060.00 at a feed concentration of 7% to IDR 20,822,633,010.00 at a concentration of 15%. From the above description, for a feed flow rate of 125,000 kg/h with a product concentration of 64%, the optimum condition is obtained with a minimum total annual production cost of IDR 20,822,633,010.00 at a feed concentration of 15% and a quadruple effect evaporator. Under these optimum conditions, the steam requirement is 23,902.42 kg/h, the steam economy is SE = 4.00, and the total heat transfer area is 2,276 m^2. If checked against the heat transfer flux, the heat flux (q/A) = 58,494,020 W/2,276 m^2 = 25,701.9 W/m^2, which is still lower than the maximum heat flux of 120,000 W/m^2 [17].

4. CONCLUSION

The optimization of heat transfer area and steam requirement can be based on the minimum total annual production cost of sugar solution (juice). For sugar solution with feed rate of 125,000 kg/h, concentration of 11%, and feed temperature of 100°C, the optimum condition with the minimum total annual production cost of juice was achieved at IDR 22,090,361,779.00 using a quadruple effect evaporator with a total evaporator heat transfer area of 2,443.81 m^2, steam economy of 3.98, and steam requirement of 26,028.2 kg/h. This condition is not far different from the number of effects typically used in most sugar factories in Indonesia, which is four effects. Results also showed that with the increase in the number of effects (from 4 to 7), the annual total sugar solution production cost will increase, along with the increase in the heat transfer area of the evaporator from 1,931 m^2 to 4,433 m^2. For various numbers of effects, increasing the feed concentration from 7% to 11% will decrease the total annual production cost of sugar solution. For a quadruple effect evaporator, the steam requirement will decrease from 28,151 kg/h at feed concentration of 7% to 23,902 kg/h at feed concentration of 15%. Furthermore, for each sugar solution feed concentration, the total annual production cost will decrease linearly. At a feed temperature of 100°C, the production cost of sugar solution will decrease from IDR 23,335,553,060.00 at a feed concentration of 7% to IDR 20,822,633,010.00 at a feed concentration of 15%.

REFERENCES

[1] H. Rusdi, W.P. Primandhana, M. Wahed, “Analisis Faktor Yang Mempengaruhi Impor Gula Di Indonesia”, Jurnal Syntax Admiration, vol. 2, no. 8, pp. 1461-1479, Agu, (2021). doi: 10.46799/jsa.v2i8.285

[2] A. S. Wijaya, M. I. Ardiansyah, D. R. Wulan dan A. Suwito, “Analisis Variabel Proses Yang Dipengaruhi Oleh Tekanan Uap Bekas Quintuple Effect System Evaporator Di PG Kedawoeng, Pasuruan”, Distilat J. Teknol. Separasi, vol. 8, no. 1, pp. 213-223, Mar (2022). doi: 10.33795/distilat.v8i1.330

[3] C. J. Geankoplis, A. A. Hersel and D. H. Lepek, “Evaporation”, in Transport Processes and Separation Process Principles, 5th ed., Boston, Pearson Education, Inc., (2018), ch. 32, sec. 32.2-32.5, pp. 1004-1026

[4] Á. L. Alarcóna, A. Orjuelaa, P. C. Narváez, E. C. Camacho, “Thermal and Rheological Properties of Juices and Syrups during Non-centrifugal Sugar Cane (Jaggery) Production”, vol. 121, no. - , pp. 76-90, Feb. (2020), doi: 10.1016/j.fbp.2020.01.016

[5] C. J. Geankoplis, A. A. Hersel and D. H. Lepek, “Physical Properties of Water”, in Transport Processes and Separation Process Principles, 5th ed., Boston, Pearson Education, Inc., (2018), Appendix A.2, sec. Appendix A.2-9a, pp. 1046-1047

[6] R. E. N. de Castro, R. M. B. Alvesa, Adam Hawkesb and C. A. O. Nascimento, “Open Sugarcane Process Simulation Platform”, Proceedings of the 13th International Symposium on Process Systems Engineering, pp. 1819-1824, July 1-5, (2018) doi: 10.1016/B978-0-444-64241-7.50298-6

[7] S. Hermanto, “Laporan Kerja Praktik”, PT PG Candi Baru, Sidoarjo, Indonesia, hlm. 85-92, repository@wima.ac.id. (2019)

[8] R. W. Serth and T. G. Lestina, “Reboilers” in Process Heat Transfer: Principles, Applications and Rules of Thumb, 3rd ed., Amsterdam, Academic Press (AP), (2014), ch. 10, sec. 10.2-10.5, p.361-394

[9] E. A. Storia, “Pengaruh Brix Terhadap Karakteristik Perpindahan Panas Pada Evaporator Robert Sistem Quintuple-Effect Di PG. Gempolkrep”, Laporan Tugas Akhir S-1, Jurusan Teknik Mesin, ITS, Surabaya, Indonesia (2019)

[10] J. R. Couper, W. R. Penny, J. R. Fair and S. M. Walas, “Heat Transfer and Heat Exchangers” in Chemical Process Equipment: Selection and Design, 3rd ed., Amsterdam, Elsevier Inc., (2012), ch. 8, sec. 8.10, pp. 201-202

[11] D. Srivastava, B. Mohanty and R. Bhargava, “Modeling and Simulation of MEE System Used in the Sugar

Industry", Chem. Eng. Comm., vol. 200, no. - , pp. 1.089-1.101, Apr. (2013). doi: 10.1080/00986445.2012.737876

[12] S. Chantasiriwan, "Online Determination of Heat Transfer Coefficients in Sugar Juice Evaporation Process", J. Food. Eng., vol. 230, no. - , pp. 63-71, Agu. (2018), doi: 10.1016/j.jfoodeng.2018.02.021

[13] R. Evizal, "Tebang-Muat-Angkut" dalam Pengelolaan Perkebunan Tebu, 1st ed., Yogyakarta, Graha Ilmu, (2018), ch. 13, sec. 13.3, pp. 215-232

[14] M. S. Peters, K.D. Timmerhaus and R. E. West, "Heat-Transfer Equipment-Design and Cost" in Plant Design and Economics for Chemical Engineers, 5th edition, p 690. Singapore, McGraw-Hill co., (2004), ch. 14, p. 690

[15] M. A. Sorour, "Optimization of Multiple Effect Evaporators Designed for Fruit Juice Concentrate", AJEE, vol. 3, no. 1, pp. 6-11, Mar, (2015). doi: 10.11648/j.ajee.s.2015030201.12

[16] J. Hanuranto dan A. Mustafa, "Pengukuran Variabel Proses Pada Quadruple Effect Evaporation Di Pabrik Gula", Majalah Ilmiah Pengkajian Industri, vol. 7, no. 1, pp. 19-26, Apr (2013). doi: 10.29122/mipi.v7i1.3640

[17] M. Nitsche, and R.O. Gbadamosi, Design of Evaporators, in "Heat Transfer Design Quide: A Practical Guide for Planning, Selecting and Designing of Shell and Tube Exchangers", Butterworth-Heinemann, (2016), Ch. 9, p 147-179, https://doi.org/10.1016/C2014-0-04971-4