The Exergetic Performance Evaluation of the Quintuple Effect Evaporator in Raw Sugar Production Processes

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Abstract

The aim of this paper was evaluation the exergetic performance of quintuple effect evaporators units in raw sugar production processes. The energy analysis in the raw sugar production process has been using basic thermodynamic principles to evaluate the performance of the quintuple effect evaporator. However, the energy principle is not enough to find out resource utilization. This study showed the exergy and advance thermodynamics analysis to evaluate quintuple effect evaporator performance for use in the improvement of the energy efficiency of system. The research was on actual processing conditions. The raw sugar production process was evaluated using key indicators to measure the effectiveness, exergy losses, exergetic efficiency of each evaporator and overall effects. The results from analysis by exergy showed that the highest exergy loss was at the first evaporator with 23,100.04 kW, 49 % of exergy input. Whereas the third evaporator had the highest exergetic efficiency with 92.40 %. Furthermore, there is moderate exergy loss at the fourth evaporator. Other effects of exergy destruction of the quintuple effect evaporator were identified. The analysis results can be used for improving energy saving, design, equipment operation and overall sugarcane production process.

Keywords:

Quintuple Effect Evaporator, Exergetic Efficiency, Raw Sugar Production, Exergy

1. Introduction

The national renewable energy plan has been targeting the development of renewable energy sources such as solar, wind and biomass, including municipal wastes and biogas. Renewable energy has become more important as opposition to clean coal technology has increased particularly from local people living in areas targeted for coal power plants. Thus, the targets for renewable energy development has been further increased to substitute coal power plants.

This is a good opportunity for the sugar industry to improve further the production of electricity from bagasse and increase the contribution to grid. An improved analysis of energy consumption and losses in the sugar production process should be reconsidered with the aim of increasing further energy efficiency. In particular, the analysis should focus on the heat transfer between the steam and the sugar cane juice, and the heat losses from the evaporators to the surroundings during the sugarcane juice thickening operation [2].

The quintuple effect evaporator unit commonly used in sugar factories is designed using energy performance criteria based on the first law of thermodynamic. The real useful energy cannot be determined using the first law of thermodynamic because it does not differentiate between the quality and quantity of energy [3], [4] and [5]. Typically, energy analysis will only show the quantities of energy.

The basic concept of exergy is to allow measurement of energy quantity, quality and the imbalance between the system and its environment [6]. It is a useful tool for determining the real efficiency of an equipment and a process, and identifying the cause, location and magnitude of inefficiencies, losses and waste [7]. The exergy cannot be conserved, but it can increase or decrease the efficiency of mass and energy transformation processes, be stored in all materials and energy flows of natural resources, such as fuels and minerals and be destroyed by not being used or by being generated as residues [8]. The exergy analysis can be done in two ways with the environment used as reference state and the exergy measured at any thermodynamic variation. Furthermore, this allows comparison between all inlet flow and outlet flow, whether mass or energy stream, by using the same principle [9] and [10].

The assessment of the energy and the exergy efficiencies of quintuple effect evaporator for raw sugar production processes aims to determine the possible increase in the quintuple effect evaporator system efficiency and decrease the quintuple effect evaporator loss of exergy. Mass, energy and exergy balances were performed for each of the processes leading to the quantification of heat, steam, waste, gas emissions and destroyed exergy. In the sugar industry, the quintuple effect evaporators are used to evaporate water from thin juice using stream to produce thick juice to become the raw syrup used for the crystallization process. The energy consumption in sugar processes is one of the most important indicators showing the performance and the efficiency of a sugar factory and its heating equipment.

The global sugar production is expected increase from 1811.6 Mt. in 2016 up to 2151.9 Mt. in 2025 [11]. As such, the Thai government has promoted increase in sugarcane production from 94,500,000 metric tons per year at present to 180,000,000 metric tons per year within the next ten years [12]. Due to this significant increase in the production volume, energy cost has become a key factor in the raw sugar production cost. Normally, the cost of raw sugar production is about 12,000 Thai baht per ton of raw sugar wherein the energy cost is 1,500 Thai baht or 12.50 % of the total production cost [13].

According to Thailand 2015 Power Development Plan, the electricity production capacity from coal for Krabi province had to increase to 870 MW and for Songkhla to 1,100 MW, but both were not achieved. Therefore, the Ministry of Energy has revised the new power development plan by increasing the share of electricity produced from renewable energy from 20% to 40% [1].

The discussions in this paper focus on the exergy being destroyed in the quintuple effect evaporator; to determine the magnitude, location and cause of irreversibility in the quintuple effect evaporator. The exergetic evaluation is done to understand the actual performance of the quintuple effect evaporator which can then lead to the identification of the process controlling parameters and the possible performance efficiency design improvements of the quintuple effect evaporator. The exergetic evaluation analysis can point to the main energy loss in the quintuple effect evaporator, the entropy generation, and the lost opportunities to do work. It can also lead to reduction of energy cost production. Lastly, the results from the quintuple effect evaporator performance evaluation can be used to improve the quintuple effect evaporator to save energy and to have surplus bagasse. This surplus bagasse can be used to generate additional renewable electricity supply to feed into grid in accordance with Power Development Plan 2015(PDP 2015) [1].

2. Raw sugar production process

Sugarcane is the raw material for raw sugar and refined sugar production. The sugarcane is crushed in the milling plant to extracts the juice with efficiencies ranging between 95% and 97% [14]. The milling residue, called bagasse, has moisture content between 45% and 55% is feed stocked for burning in the boiler [15]. The thin juice go through the clarification and concentration process in the clarifiers and evaporators. The evaporators concentrate the thin juice into a syrup by evaporating the water using heat from exhaust steam. The highly concentrated syrup is then delivered into the vacuum pans. The vacuum pans raise the syrup concentration to crystallize zone using bled vapour from first and second effect evaporators. In this process, it takes two and six hours of boiling time for sugar crystal to grow depending on the grade of the sugar. Sugars from the boiling process are generally referred to as a massecuite. After boiling, the massecuite are then taken for separation of the molasses from the sugar crystals by using centrifugal machines. The centrifugal machines use gravity force to separate the sugar crystals from the molasses. After the separation process, the raw sugar goes for drying and cooling processes. The dryer and cooler reduced the moisture and temperature of the raw sugar to meet the product specifications for raw sugar. Usually, the drying and cooling processes reduce the raw sugar moisture content from 0.50 % to 0.25 % [16] and reduce the raw sugar temperature from 50 °C to 35 °C [16]. The dried raw sugar leaving the dryer and cooler should be of product quality required for storage in warehouses waiting for delivery to customers. The flow diagram for raw sugar production is shown in Fig. 1. The juice evaporation is done using the quintuple effect evaporator.

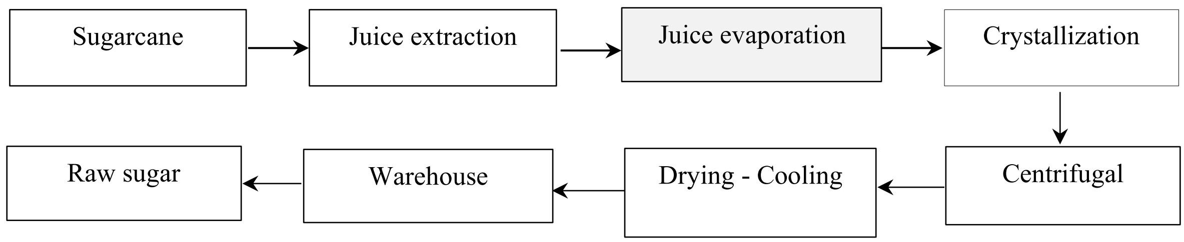

Fig. 1 Raw sugar production process.

3. Quintuple effect evaporator

The schematic diagram of the quintuple effect evaporator is shown in Figure 2. The quintuple effect evaporator is for increasing the concentration of the thin juice from 14 % to 68 % solid content. The quintuple effect evaporator requires a supply of exhaust steam from the steam turbines to evaporate the water from the thin juice. The generated vapour from the last evaporator then goes to the condenser [17]. The quintuple effect evaporator consists of five evaporators, in which one kg of steam is used to vaporize five kg of water. If the vapour withdrawn from each evaporator is used outside the evaporator system in place of steam, the steam that will be saved in this sequence of evaporators will be divided by the number of evaporators times the quantity of steam used. The thin juice entering the quintuple effect evaporator at the first stage takes place at constant pressure, the solution is drawn into the first stage at atmospheric pressure and vapour is taken from the first stage to next stage for heating at each process [18].

4. Experiment model and exergy analysis

4.1. Experiment model

A Tubular rising film Robert type quintuple effect evaporator was used is this study. Fig. 2 shows the schematic representation of the quintuple effect evaporator with the bleeding and flash tanks.

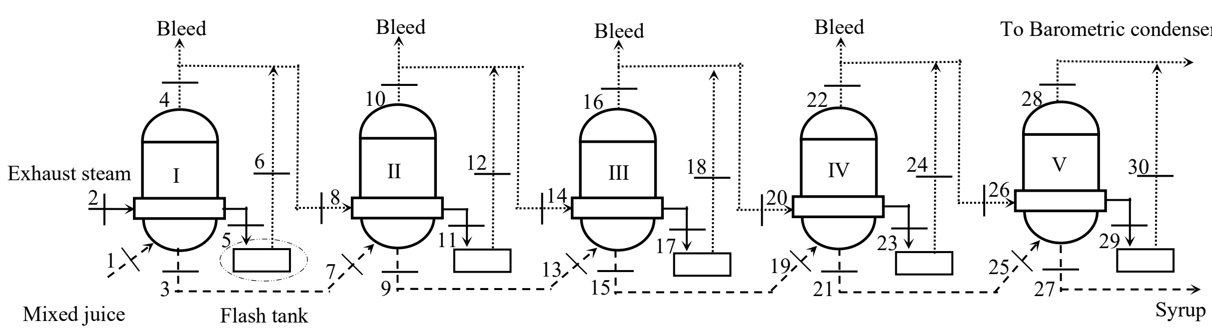

Fig. 2 Quintuple effect evaporator.

4.2. Exergy analysis

- The general exergy balance to control the volume at steady state is expressed as below [19]:

$$\dot{E}x_{dest.} = \sum\left[1 - \frac{T_0}{T}\right]Q - \dot{W} + \Sigma\, \dot{m}_{in}\, ex_{in} - \Sigma \dot{m}_{out}\, ex_{out} \tag{1}$$

- The specific flow exergy can be expressed by equation the below [20]:

$$ex = (h - h_0) - T_0\,(s - s_0) \tag{2}$$

- The specific exergy flow for incompressible flow is given by equation the below [21]:

$$ex_{in} = C\left[(T - T_0) - T_0 \ln\left\{\frac{T_0}{T}\right\}\right] \tag{3}$$

- The total exergy can be determined as below [22]:

$$\dot{E}x = ex.m \tag{4}$$

- In the present context the exergy balance for exergy destruction in the quintuple effect evaporator is given as below [22]:

$$\dot{E}x_{steam} + \dot{E}x_{juice,in} = \dot{E}x_{dest.} + \dot{E}x_{juice,out} + \dot{E}x_{cond.} + \dot{E}x_{evap.} \tag{5}$$

- The exergy destruction at each evaporator for the quintuple effect evaporator are given below [22].

$$\dot{E}x_{dest.I} = \dot{E}x_1 + \dot{E}x_2 - \dot{E}x_3 - \dot{E}x_4 - \dot{E}x_5 \tag{6}$$

$$\dot{E}x_{dest.II} = \dot{E}x_6 + \dot{E}x_7 + \dot{E}x_8 - \dot{E}x_9 - \dot{E}x_{10} - \dot{E}x_{11} \tag{7}$$

$$\dot{E}x_{dest.III} = \dot{E}x_{12} + \dot{E}x_{13} + \dot{E}x_{14} - \dot{E}x_{15} - \dot{E}x_{16} - \dot{E}x_{17} \tag{8}$$

$$\dot{E}x_{dest.IV} = \dot{E}x_{18} + \dot{E}x_{19} + \dot{E}x_{20} - \dot{E}x_{21} - \dot{E}x_{22} - \dot{E}x_{23} \tag{9}$$

$$\dot{E}x_{dest.V} = \dot{E}x_{24} + \dot{E}x_{25} + \dot{E}x_{26} - \dot{E}x_{27} - \dot{E}x_{28} - \dot{E}x_{29} \tag{10}$$

- Exegetic efficiency of the quintuple effect evaporator is given equation as below [23].

$$\eta_{ex} = \frac{\dot{E}x_{cold,out} - \dot{E}x_{cold,in}}{\dot{E}x_{hot,in} - \dot{E}x_{hot,out}} = \frac{\Delta\dot{E}x_{cold}}{\Delta\dot{E}x_{hot}} \tag{11}$$

- Improvement potential of the quintuple effect evaporator is given equation as below [24].

$$IP = (1 - \eta_{ex})(\dot{E}x_{in} - \dot{E}x_{out}) \tag{12}$$

4.3. Results of exergy analysis

The results of exergy analysis are calculated using real process and controlling parameters as below.

Table 1 The exergy analysis (Based on 30 ºC reference temperature, juice temperature 105 ºC, juice brix 14.00 and syrup brix 62.00).

Evaporator	**1st evaporator**	**2nd evaporator**	**3rd evaporator**	**4th evaporator**	**5th evaporator**
Exergy dest. (*kW*)	23071.60	8613.58	5171.95	6839.12	3232.36
Exergy eff.; η (%)	55.82	87.32	92.16	66.08	75.69
Juice in (%)	14.00	19.81	26.06	34.32	46.93
Juice out (%)	19.81	26.06	34.32	46.93	62.00
Brix increase (%)	41.49	31.58	31.68	36.75	32.10

Table 2 The exergy analysis (Based on 30 ºC reference temperature, juice temperature 105 ºC, juice brix 15.50 and syrup brix 62.00).

Evaporator	**1st evaporator**	**2nd evaporator**	**3rd evaporator**	**4th evaporator**	**5th evaporator**
Exergy dest. (*kW*)	22968.04	8500.08	5097.44	6756.92	3087.37
Exergy eff.; η (%)	55.00	86.90	91.82	65.05	77.25
Juice in (%)	15.50	21.76	28.30	36.62	48.71
Juice out (%)	21.76	28.30	36.62	48.71	62.00
Brix increase (%)	40.42	30.03	29.40	33.00	27.29

Table 3 The exergy analysis (Based on 30 ºC reference temperature, juice temperature 112 ºC, juice brix 14.00 and syrup brix 62.00).

Evaporator	**1st evaporator**	**2nd evaporator**	**3rd evaporator**	**4th evaporator**	**5th evaporator**
Exergy dest. (*kW*)	22867.25	8613.58	5171.95	6839.12	3232.36
Exergy eff.; η (%)	61.79	87.32	92.16	66.08	75.69
Juice in (%)	14.00	19.81	26.06	34.32	46.93
Juice out (%)	19.81	26.06	34.32	46.93	62.00
Brix increase (%)	41.49	31.58	31.68	36.75	32.10

Table 4 The exergy analysis (Based on 30 ºC reference temperature, juice temperature 112 ºC, juice brix 15.50.00 and syrup brix 62.00).

Evaporator	1st evaporator	2nd evaporator	3rd evaporator	4th evaporator	5th evaporator
Exergy dest. (*kW*)	22765.70	8500.80	5097.44	6756.92	3087.37
Exergy eff.; η (%)	60.99	86.90	91.82	65.05	77.25
Juice in (%)	15.50	21.76	28.30	36.62	48.71
Juice out (%)	21.76	28.30	36.62	48.71	62.00
Brix increase (%)	40.42	30.03	29.40	33.00	27.29

Table 5 The exergy analysis (Based on 30 ºC reference temperature, juice temperature 105 ºC, juice brix 14.00 and syrup brix 68.00).

Evaporator	1st evaporator	2nd evaporator	3rd evaporator	4th evaporator	5th evaporator
Exergy dest. (*kW*)	23100.04	8635.57	5193.51	6844.44	3360.46
Exergy eff.; η (%)	56.52	87.80	92.40	67.18	74.04
Juice in (%)	14.00	19.92	26.46	35.36	49.58
Juice out (%)	19.92	26.46	35.36	49.58	68.00
Brix increase (%)	42.30	32.81	33.64	40.42	37.14

Table 6 The exergy analysis (Based on 30 ºC reference temperature, juice temperature 105 ºC, juice brix 15.50 and syrup brix 68.00).

Evaporator	1st evaporator	2nd evaporator	3rd evaporator	4th evaporator	5th evaporator
Exergy dest. (*kW*)	22999.48	8524.62	5120.77	6763.89	3229.83
Exergy eff.; η (%)	55.81	87.46	92.11	66.35	75.19
Juice in (%)	15.50	21.90	28.76	37.80	51.57
Juice out (%)	21.90	28.76	37.80	51.57	68.00
Brix increase (%)	41.29	31.34	31.43	36.41	31.87

Table 7 The exergy analysis (Based on 30 ºC reference temperature, juice temperature 112 ºC, juice brix 14.00 and syrup brix 68.00).

Evaporator	1st evaporator	2nd evaporator	3rd evaporator	4th evaporator	5th evaporator
Exergy dest. (*kW*)	22895.69	8635.57	5193.51	6844.44	3360.46
Exergy eff.; η (%)	62.44	87.80	92.40	67.18	74.04
Juice in (%)	14.00	19.92	26.46	35.36	49.58
Juice out (%)	19.92	26.46	35.36	49.58	68.00
Brix increase (%)	42.30	32.81	33.64	40.24	37.14

Table 8 The exergy analysis (Based on 30 ºC reference temperature, juice temperature 112 ºC, juice brix 15.50 and syrup brix 68.00).

Evaporator	1st evaporator	2nd evaporator	3rd evaporator	4th evaporator	5th evaporator
Exergy dest. (*kW*)	22797.13	8524.62	5120.77	6763.89	3229.83
Exergy eff.; η (*%*)	61.73	87.46	92.11	66.35	75.19
Juice in (*%*)	15.50	21.90	28.76	37.80	51.57
Juice out (*%*)	21.90	28.76	37.80	51.57	68.00
Brix increase (*%*)	41.29	31.34	31.43	36.41	31.87

5. Results and discussions

Table 1 to table 8 shows the results of the exergies analysis based on the experimental values in the analysis of the operation of the quintuple effect evaporator; the difference in juice temperature, the juice brix entering the first effect evaporator and the difference of the values of the syrup brix leaving from the last evaporator at the reference temperature of 30 ºC. Each evaporator in the quintuple effect evaporator is analysed according to the first and second law of thermodynamics. The juice brix leaving from each evaporator obtained would indicate quality of feed stock for crystallization. In each evaporator of the quintuple effect evaporator, the changes of performance parameters are the results of the various of states of raw sugar production process. The cause is changed of entropy generated in the quintuple effect evaporator during evaporation water process. The various of evaporation process at each evaporator are the results of the juice brix changes from 14.00 % brix to 68.00 % brix. The results at each evaporator are given in detail below.

First evaporator of the quintuple effect evaporator

The highest value of exergy destruction takes place in the first evaporator. The highest exergy destruction amount is 23,100.04 kW as shown on Table 5. This exergy accounts for 49% of total exergy loss and destruction in the quintuple effect evaporator. There is also a potential improvement to increase the efficiency of the quintuple effect evaporator by about 10809.75 kW. The lowest exergetic efficiency is found to be 55.00 % as shown on Table 2. The amount of exergetic efficiency is very low compare with other exergetic efficiencies. The cause of the low exergetic efficiency is due to the high temperature of the exhaust steam supply to the first evaporator and the high temperature difference between juice inlet temperature with the exhaust steam temperature (ΔT=120 -105 =15ºC). Both cases of high exergy loss and low exergetic efficiency can be improved by increasing juice temperature inlet close to the boiling point of the sucrose solution, by increasing the inlet juice brix to the highest possible level but without affecting the process and equipment. In addition, the exhaust steam temperature is decreased to the nearest or equal to the criteria design of the quintuple effect evaporator. The insulation of equipment also helps to reduce heat loss. However, the high pressure drop at the vapor inlet and vapor outlet of first evaporator is another cause of high exergy destruction and low exergetic efficiency (ΔP = 2.033 -1.631 = 0.402 bar A).

Second evaporator of the quintuple effect evaporator

The exergy destruction in the second evaporator of the quintuple effect evaporator is 8635.57 kW as shown in Tables 5 and 7. In this evaporator the temperature difference between input juice and boiling point elevation of sucrose solution is narrow (ΔT=113 -105.79 = 7.21 ºC). There is small range of potential improvement of around 690. 86 kW.

Third evaporator of the quintuple effect evaporator

The best exergetic efficiency of third evaporator of the quintuple effect evaporator is 92.40 % as shown n Tables 5 and 7 and the low exergy destruction indicated is 5097 kW as shown in Tables 2 and e 4. The root cause of perfect exergetic efficiency of the third evaporator is that the difference of the temperature between the juice inlet temperature and boiling point of the sucrose solution is very small (ΔT=105.79 - 105.00 = 0.79 °C). Conversely, the improvement potential of this evaporator will at least be 152.92 kW. In addition, the low pressure drop of the vapor inlet and the vapor outlet of third evaporator is one cause of having the highest exergetic efficiency and low exergy destruction (ΔP =1.25 - 0.88 = 0.37 bar A).

Fourth evaporator of the quintuple effect evaporator

In fourth evaporator the exergetic efficiency is lower by 65.05 % than the first evaporator as shown on Tables 2 and 4. There is a potential slight improvement of efficiency in the fourth evaporator of about 1891.94 kW.

Fifth evaporator of the quintuple effect evaporator

The lowest exegetic efficiency of this evaporator is 74.04 % as shown in Tables 5 and le 7. There small potential of efficiency improvement of 436.86 kW.

6. Conclusion and recommendations

The methodology for the exergetic performance evaluation of the quintuple effect evaporator for raw sugar production has been determined and applied to study the different controlling parameters. The exergy destruction l took place at the first evaporator, with the lowest exergy lost value that was caused by increasing the temperature of the thin juice to 112 °C, and increasing the brix of the thin juice to 15.50 brix. Under the same method the maximum exergetic efficiency also occurred at the first evaporator.

This experiment suggests that the temperature of thin juice must be increased to equal or close to the boiling point of the sucrose solution. This will reduce significant exergy destruction and increase exergetic efficiency. In addition, the higher intensity of the thin juice will reduce exergy loss. But, nowadays, in practice, there is no right way or appropriate solution to reduce exergy losses in multi effect evaporators.

Sugarcane is typically composed of 70 % water depending on the variety of the sugarcane and the source countries. Applying renewable energy using bagasse from the sugarcane processing is an option to save energy but it cannot reduce exergy destruction directly. In addition, the use of special evaporators such as plate evaporators and long tubes evaporators cannot help reduce exergy destruction in evaporators, but only to reduce inversion loss during the evaporation process.

List of Abbreviations and Symbols

C = specific heat
eff = efficiency
$\dot{E}x$ = exergy rate (kJ/mpb)
ex = specific flow energy (kJ/mpb)
h = specific enthalpy (kJ/kg)
$\dot{m}$ = mass flow rate (kg/mpb)
Q = heat (kJ)
S = specific entropy (kJ/kgK)
T = temperature (K)
ΔT = temperature difference (K)
$\dot{W}$ = electricity energy (kWh)
IP = Improvement potential

Subscripts

cond.	= condenser
dest.	= destruction
ex	= exergy
evap.	= evaporator
in	= inflow
out	= outflow
mpb	= 100 kg of beet in 1 min

Greek letters

η	= efficiency
Δ	= difference

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