Reaktor

p-ISSN 0852 – 0798
e-ISSN 2407 – 5973

Website : http://ejournal.undip.ac.id/index.php/reaktor/

Reaktor, Vol. 21 No. 2, June Year 2021, pp. 74-93

Thermal Integration Analysis and Improved Configuration for Multiple Effect Evaporator System Based on Pinch Analysis

Indra Riadi[1*], Zulfan Adi Putra[2], Heri Cahyono[3]

[1]Department of Engineering Procurement and Construction, PT. Adhi Karya (Persero), Tbk, Jakarta, Indonesia
[2]PETRONAS Group Technical Solutions (Process Simulation and Optimization), Kuala Lumpur, 50088, Malaysia
[3]Department of Chemical Engineering, Faculty of Engineering, Diponegoro University, Postal Code 50239, Semarang, Indonesia

Corresponding authors: indra.riadi@adhi.co.id

(Received : April 08, 2021; Accepted: August 08, 2021)

Abstract

Pinch analysis for a sugar plant production capacity 4000 TCD has been carried out to reduce its energy consumptions. The plant has ten evaporators that can be configured to several multiple effect evaporators. It has been running with five-effect evaporator (quintuple) scheme. To maximize energy utilization within the plant, three multiple effect evaporator schemes were evaluated. They are triple effect evaporator, quadruple effect evaporator, and quintuple effect evaporator as the benchmark. The result shows that the quintuple effect evaporator yields the highest energy efficiency by about 8% compared to existing configuration. The chosen options to achieve such target is to use low pressure steam only for the first effect and to use steam bleeding from the first effect to heat a tertiary juice heater. With this proposed scenario, sugar dryer, wash water RVF unit and wash water HGF unit no longer need external steam for its operation.

Keywords: *Sugar plant, multiple effect evaporator, process integration, heat exchanger network, pinch analysis*

How to Cite This Article: Riadi, I., Putra Z. A., and Cahyono, H., (2021), Thermal Integration Analysis and Improved Configuration for Multiple Effect Evaporator System Based on Pinch Analysis, Reaktor, 21(2), 74-93, https://doi.org/10.14710/reaktor.21.2.74-93

INTRODUCTION

In a typical sugar plant, juice heating, evaporation, and crystallization units are main process units that require heat input. Among them, evaporator is used to reduce water content in purified cane juices into a high concentrated syrup. This evaporation process obviously needs a large amount of energy. However, the units can be heat-integrated in such a way that the generated vapor from one stage can be used to heat the other stage (Higa *et al*, 2009).

Heat and resource recovery has been frequently investigated in chemical industries using various approaches. Much research has been published to improve system based production efficiency, incluing the heat and power cogeneration system(Y. Li *et al*., 2018), manufacture (Gautami *et al*, 2012) and waste heat recovery technologies (Safder *et al*, 2019) . Due to its importance in the plant-wide energy consumption, the energy requirement of the evaporation process is generally evaluated via pinch analysis. Pinch analysis is a common method to optimize the energy system. It is generally used to evaluate the potentials for reducing the amount of external heating and cooling utilities via composite curves (CC) and Grand Composite Curve (GCC) (Linnhoff *et al*., 1982) and ((Kemp, 2007).

The development and applications of heat integration in sugar plants have been widely reported. (Umar *et al*, 2017) analyzed energy integration in Savannah sugar company with quadruple effect evaporator and proposed the best heat exchanger network. (Higa *et al*, 2009) has successfully developed thermal integration equations of various multiple effect evaporator configurations that can be used as reference for thermal integration projects. The equations are also helpful for elaborating a systematic way to apply pinch analysis in sugar plant with an algorithm. (Safder *et al*, 2020) reported chemical exergy pinch analysis could efficiently provide the optimal pressure retarded osmosis retrofitted industrial networks for decisionmaking. (Lambert *et al*, 2018) studied a generic methodology to model food processes to in fine allow Pinch and exergy analys is proposed by ProSimPlus software.

Its operating conditions definitely affect the evaporation rates of juice and vapor bleeding productions. Vapor bleeding is basically the water vapor produced from in the evaporator (Blanco *et al*, 2012). Inadequate operating condition will lead to a lower concentration and thicker juice resulting in a higher load in the subsequent crystallization unit. This situation may lead to the production stop. The other consequence is that the amount of evaporated water is not as it should be, and hence, the plant requires more steam from its boiler unit. Then, the fuel supplied to the boiler will increase. The boiler itself obviously has a certain capacity or Maximum Continuous Rate (MCR). If the required steam is higher than this limit, then the plant has to be operated at a lower production rate.

One important variable determining the energy efficiency in a sugar plant is what is called as Steam On Cane (SOC). SOC is the ratio of the amount of steam produced by the boiler to the rate of cane crushing. Once the cane is crushed and milled, the resulting fibrous residue is called bagasse, which is generally used as the source of fuel in the plant. Currently, several sugar plants in East Java, Indonesia, experiences that their bagasse are no longer sufficient to meet the needs of their energy source (Rosyid *et al*, 2008). It clearly shows a high rate of SOC and the excessive use of steam. In this work, sugar plant A located in Central Java, Indonesia, was expanded to increase its production capacity from 2500 to 4000 tons cane per day (TCD). One of the main constraints was that the SOC should be lower or equal to 45%.

To achieve this target, a proper analysis of energy usages, finding optimum operating conditions of the evaporators, and finally, the selection of best configuration of Multiple Effect Evaporator (MEE) are necessary. Hence, the aims of this study were to find the best configuration of MEE and its optimum operating condition via pinch analysis.

MODEL DEVELOPMENT

Figure 1. shows a process flow diagram of sugar plant with a sulphitation process. Juice coming from a milling station at a low brix (suspended solids) concentration (~ 11 – 12 wt%) is fed to a primary juice heater (JH 1) to reach a temperature of 75ºC. The juice is then added with lime and gas SO2 to be purified or sulfitated or defecated. The sulfitated juice is heated to a secondary juice heater (JH II) to reach temperature of 105ºC and then fed to a clarifier. The separated clear liquid juice from the clarifier is then heated in a tertiary juice heater (JH III) up to 105ºC to reach its saturated condition. Then, it is fed to an evaporation train to meet a high brix concentration of about 64 wt%, which is called as the thick juice.

In this work, the working methodology is shown in Figure 2. The plant has ten evaporators that can be configured to several multiple effect evaporators. It has been running with five-effect evaporator (quintuple) scheme as shown in Figure 7. The first step is to collect data design and operational data. The data collected are 1) Operating condition: the juice flow, the juice concentration, temperature, and pressure at each stage of the process. 2) Process configuration, 3) Heating surface evaporator existing condition

The second step is to calculate the energy requirements of the existing plant and three new configurations to be evaluated also to determine the type of stream (cold or hot). The three configurations are triple effect evaporator, quadruple effect evaporator, and quintuple effect evaporator. The result of this step is a stream data extraction table for resource conservation to determine a system's source and sinks (Gadalla, 2015).

The third step is analysis by pinch method. After getting stream extraction is to make temperature interval. The actual temperature in each stream is replaced by shifted temperature. Cold stream that needs to be heated have a shifted temperature above actual temperature. While hot stream that need to be cooled have a shifted temperature below actual temperature (Linnhoff *et al*., 1982) and (Kemp, 2007). Each interval will have a surplus or deficit of energy that depends on amount of heat capacity flowrate of each interval. After setting temperature interval, problem table, grand composite curve (GCC), composite curve (CC) and Heat Exchanger Network (HEN) can be developed. The results of this step are:

1. Pinch point
2. Composite Curve (CC)
3. Grand Composite Curve (GCC)
4. Maximum Energy Recovery (MER)
5. Hot Utility Energy
6. Cold Utility Energy
7. Heat Exchanger Network (HEN)

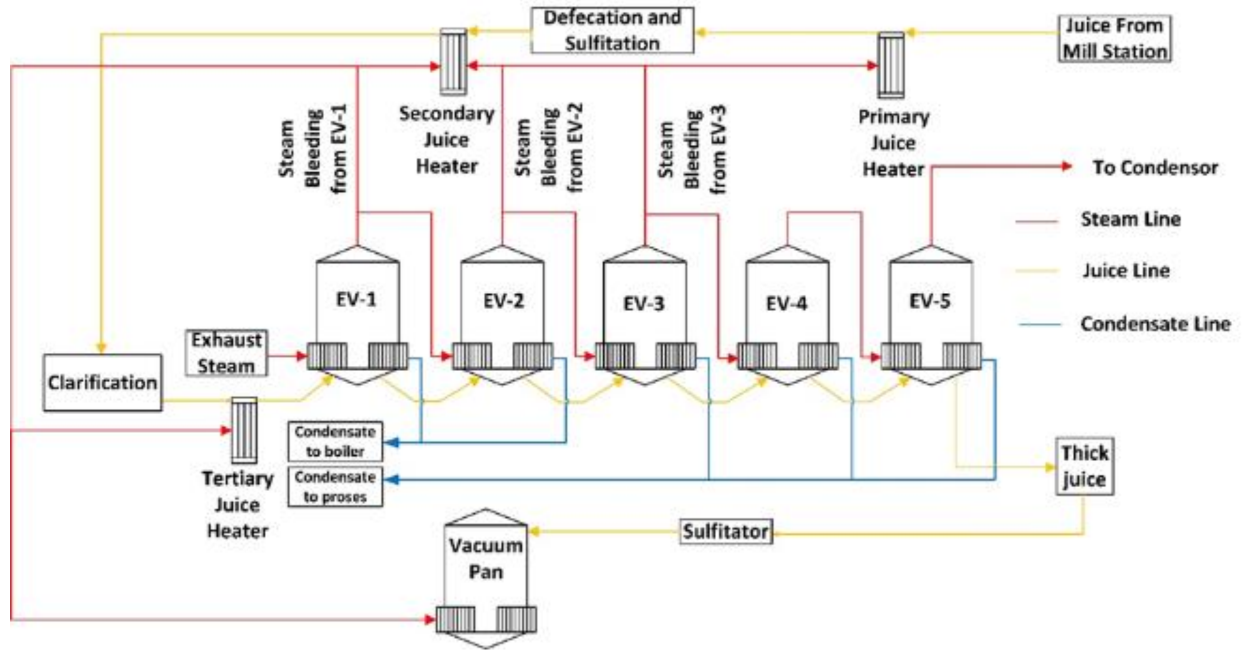

Figure 1. Process Flow Diagram Sulphitation Process Sugar Production

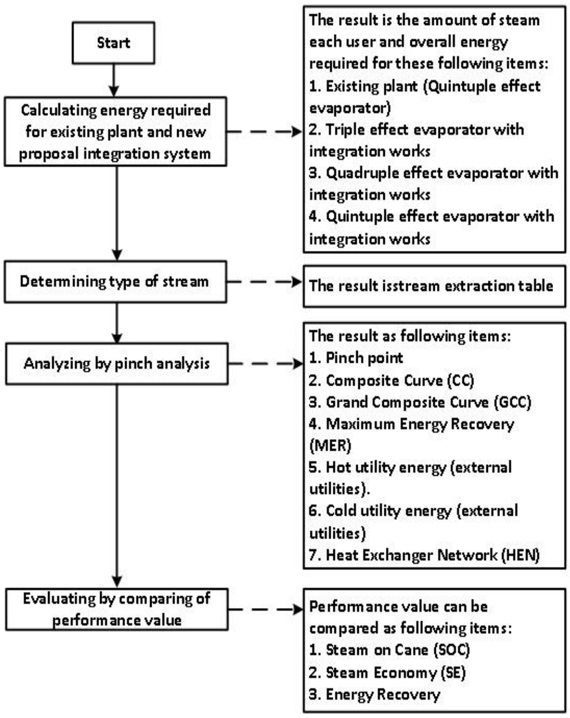

Figure 2. Flow chart of works methodology

The fourth step is evaluation by comparing the performance in each configuration.

The performance values are:

1. Steam On Cane (SOC)

Steam On Cane is the ratio of the amount of steam produced by the boiler to the rate of cane crushing (Singh *et al*, 1997).

$$SOC = \frac{Steam\ produced\ (ton/hr)}{rate\ of\ cane\ crushing\ (ton/hr)} x100\% \qquad (1)$$

2. Steam Economy (SE)

Steam Economy is the comparison of amount of evaporated water to amount of external steam used to evaporate the water (Chantasiriwan, 2017).

$$SE = \frac{Evaporated\ water\ in\ Evaporator\ (ton/hr)}{External\ steam\ \ (ton/hr)} \qquad (2)$$

3. Maximum Energy Recovery (MER)

From development of problem table, pinch point, hot utilities (QHmin), cold utilities (Qcmin) and maximum energy recovery can be identified explicitly.

4. Minimum heating surface

To find minimum heating surface each evaporator. (E.hugot, 1986) has formulated a correlation between heating surface and evaporation capacity of evaporator effect I as shown in Eq (4)

5. $$Si = \frac{Vev_i}{C\Delta Ti} \qquad (3)$$

Where Si is heating surface evaporator effect i, Vevi is evaporation capacity evaporator effect i, C is spesific evaporation coefficient and ΔT is temperature drop evaporator effect i.

Heating surface for each effect at various configuration will be calculated. If the minimum heating surface is lower than the existing condition, then this configuration can be applied.

Multiple effect evaporator

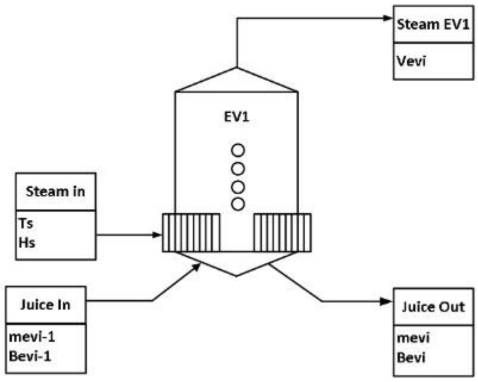

Figure 3. Evaporator effect i

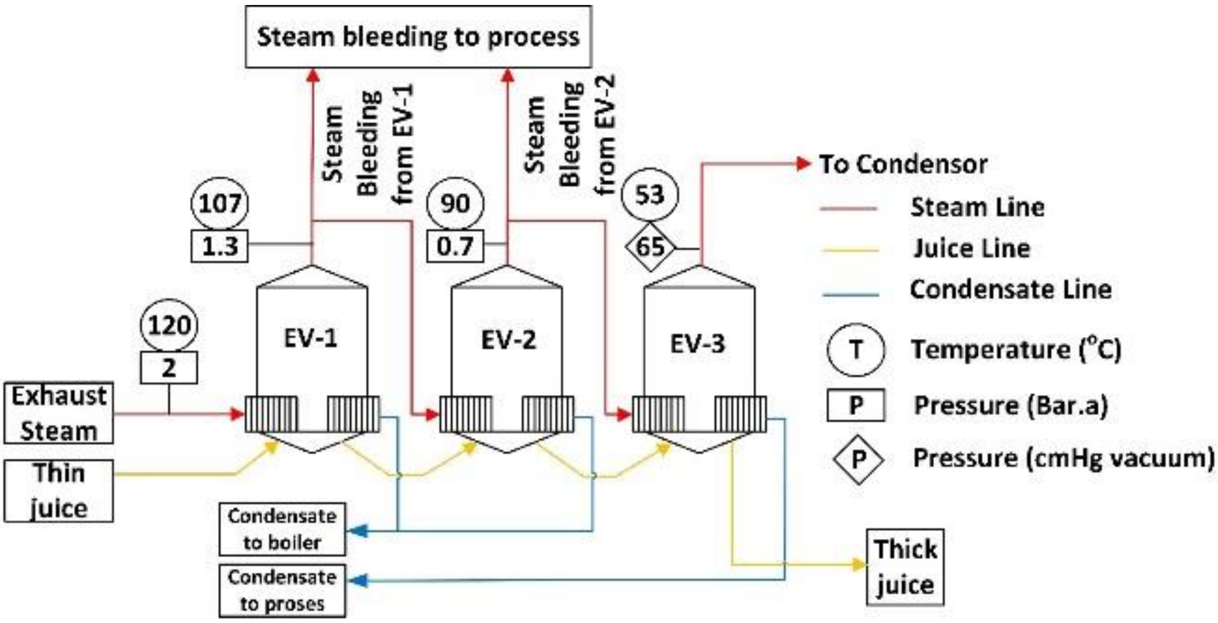

Figure 4. MEE Triple Effect Evaporator

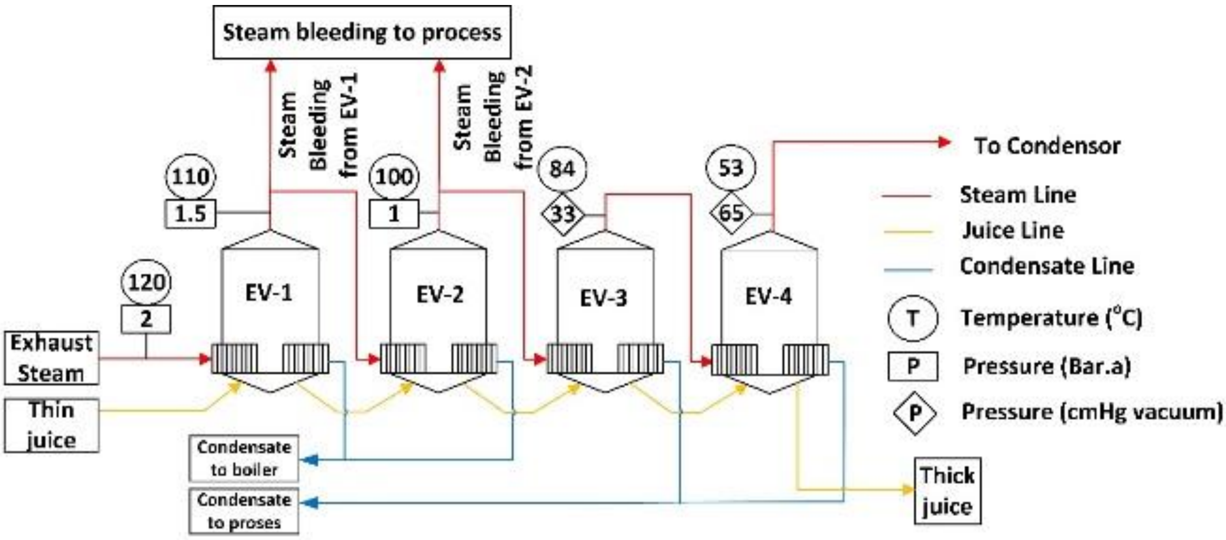

Figure 5. MEE Quadruple Effect Evaporator

Mathematical models on evaporator effect i can be described by mass balance equation (Eq (4)) (Burke, 2014) as shown in Figure 3.

$$mev_{i-1}\ x\ Bev_{i-1} = Vev_i + mev_i\ x\ Bev_i \qquad (4)$$

Where mevi-1 is flowrate of juice entering evaporator effect i, Bevi-1 is brix of juice entering evaporator effect i, Vevi is flowrate of produced vapour from evaporator effect i, mevi is flowrate of juice leaving evaporator effect i, and Bevi is brix of juice leaving evaporator effect i.

To determine pressure on each evaporator, (E.hugot, 1986) has formulated a correlation between input pressure and final pressure. Thus, operating condition each evaporator can be developed. Table 1 shows temperature in effect i evaporator with various MEE configurations at exhaust steam pressure 1 bar G (T = 120ºC). Regarding MEE configuration, each configuration can be shown in Figure 4. MEE triple effect evaporator, Figure 5. MEE quadruple effect evaporator, Figure 6. MEE quintuple effect evaporator.

Table 1. Temperature data according to effect number

Multiple effect evaporator	Effects Temperature				
	1	2	3	4	5
Triple	107	89.5	53	-	-
Quadruple	111	100	84	53	-
Quintuple	113	105	94	80	53

Because steam in saturation condition, the pressure in each stage follows saturation temperature. So that produced energy at each evaporator is latent energy. To complete degree of freedom in MEE, constant data are obtained as shown in Table 2.

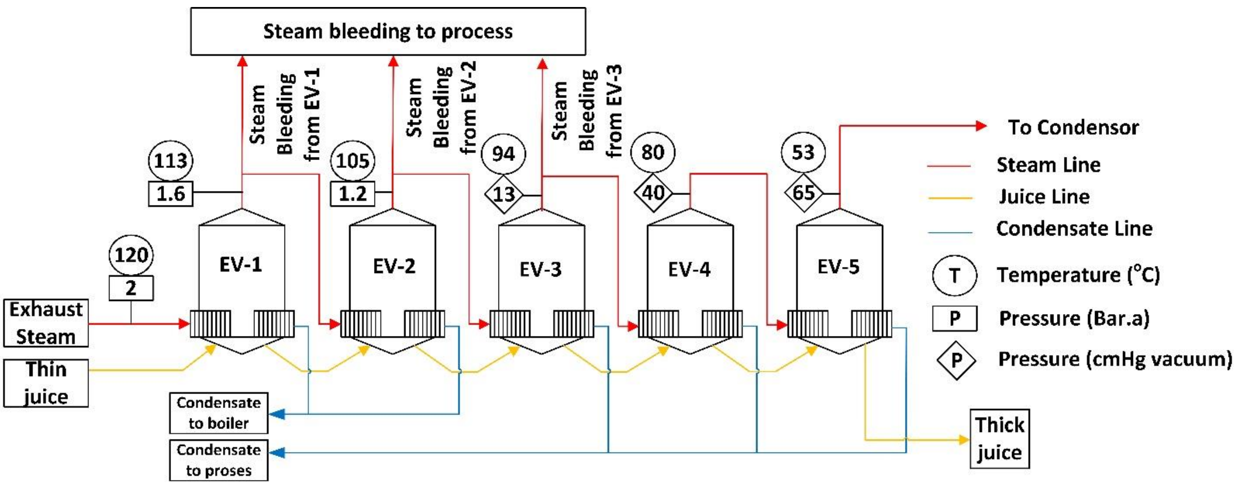

Figure 6. MEE Quintuple Effect Evaporator

Table 2. Constant data for MEE

Data	Value	Unit
Capacity	4000	TCD
Clear Juice flow	109.72	% cane
%brix clear juice	11.6	% brix
Pressure exhaust steam from steam turbine	2	Kg/cm^2.a
%brix thick juice	64	% brix

To find C (spesific evaporation coefficient), (E.hugot, 1986) has formulated an equation as shown in eq (5).

$$C = 0.001\ (100 - Bi)\ x\ (T - 54) \qquad (5)$$

Where Bi is brix concentration leaving evaporator effect i and T is temperature of steam evaporator effect i.

Boiling point rise of the juice can occur due to brix concentration of the juice. (E.hugot, 1986) has formulated as shown in Eq (6).

$$e = \frac{2B}{100-B} \qquad (6)$$

Where e is boiling point rise (in ºC) and B is concentration of the juice in %brix.

Table 3. Existing data heating surface of evaporator

Evaporator no	Heating surface (m2)
1	2000
2	2000
3	2000
4	1200
5	1200
6	1200
7	900
8	900
9	900
10	900

The vapour and juice in *i*th effect are in equilibrium and the relation for the liquor and vapor temperature defined in terms of BPR (Kumar *et al*, 2013) is as follows:

$$Tli = Tvi + ei \tag{7}$$

Juice Heater

The value of latent heat condensation of vapour bleeding is equal to the value of heat sensible of raising temperature of the juice in juice heater. The equation can be formulated as shown in Eq (8).

$$Vev_j \; x \; hev_j \; = mJ_i \; x \; C_{pi} \; x \; (TJH_i - TJH_{i-1}) \tag{8}$$

Where Cpi is average heat capacity of the juice between TJHi and TJHi-1. (Hugot, 1986) has formulated heat capacity of the juice as shown in Eq (9).

$$cp_i = 1 - [0{,}6 - 0.0018t + 0.0008\,(100 - P)]\,\frac{B}{100} \tag{9}$$

Where P is purity of the juice, t is temperature of the juice and B is brix concentration of the juice. To complete degree of freedom at each juice heater, constant datas are obtained as shown in Table 4.

Table 4. Constant data for juice heater

Data	Value	Unit
Mixed juice flow rate	120.06	%cane
Sulphited juice flow rate	123	%cane
Clear juice flow rate	109.72	%cane
%brix mixed juice	12.67	%brix
%brix sulphited juice	12.37	%brix
%brix clear juice	11.6	%brix

Vacuum Pan

Crystallization process was carried out in three stages: Pan A crystallization to produce massecuite A with brix concentration 95.22%, pan C crystallization to produce massecuite C with brix concentration 98.26% and pan D crystallization to produce massecuite D with brix concentration 99.2%. To compelete degree of freedom at each vacuum pan, constant datas are obtained as shown in Table 4. Constant data vacuum pan A, Table 5. Constant data vacuum pan C, Table 6. Constant data vacuum pan D.

Table 5. Constant data for vacuum pan A

Massecuite A feed	Brix consentration	Flow %cane
Condensate for washing massecuite A	0	1.77
Thick juice	64	Thick juice from last evaporator
A wash molasses	80.39	1.73
High remelt	78	0.1
Magma C	92.5	2.7
Magma D-2	93.6	0.19

Table 6. Constant data for vacuum pan C

Massecuite C feed	Brix consentration	Flow %cane
Condensate for washing massecuite C	0	0.65
A molasses	85	3.82
Magma D-2	93.6	3.32

To achieve brix concentration of each massecuite, required steam for each vacuum pan as shown in Eq (10), mass balance in a single evaporation has been proposed by (Geankoplis, 1993).

Table 7. Constant data for vacuum pan D

Massecuite D feed	Brix consentration	Flow %cane
Condensate for washing massecuite D	0	0.87
A molasses	80.39	5
C molasses	84	4.6
D wash molasses	80.56	0.64

$$F_i h_{fi} + S_i \lambda_i = L_i h_{Li} + V_i H_{Vi} \tag{10}$$

Where F is flow feed for massecuite i, hfi is enthalpy feed at spesific temperature, Si is flow vapour to boil feed into massecuite, λi is latent energy of steam input, Li is flow massecuite, hLi is enthalpy of massecuite i, Vi is evaporation capacity from vacuum pan i and Hvi is enthalphy of juice vapour. To obtain enthalphy of juice vapour as shown in Eq (11).

$$H_{Vi} = HS_i + cp_{sh} BPR_i \tag{11}$$

Where HSi is enthalphy of saturated vapour and cpsh is heat capacity superheated vapour.

RESULTS AND DISCUSSION

Algorithm of Mass and Heat Balance Calculation

After careful derivation of equation for each model of the system a detailed procedure is proposed to obtain the solution. Each configuration of MEE will be calculated by following step to extract process stream data:

Step 1: Values of known parameters are collected from table 1-7.

Step 2: Calculate temperature and pressure of steam each effect of evaporator based on table 1 and calculated in figure 4-6.

Step 3: Calculate steam required for each user from vapour bleeding of evaporator based on process flow diagram figure 7, figure 12, figure 16, and figure 20. In this step mass and heat balance will be generated and showed in table 11.

Step 4: Calculate temperature of juice in each effect of evaporator by considering BPR.

Step 5: Steam economy and steam on cane are computed (table 15).

Step 6: Heating surface each effect evaporator is computed (table 14).

Step 7: Process stream data is extracted on table 8, table 9 and table 10.
Summary of the calculation mass and heat balance can be seen in table 11.

Stream Data Extraction

Calculation of mass balance MEE at 4000 TCD plant capacity has been carried out, so that process data and stream data have been classified into two types based on heating and cooling demands. Case study calculations are performed with different MEE configurations: MEE triple effect configurations, MEE Quadruple effect configurations, MEE Quintuple effect configurations. Each stream data can be seen in Table 8 for triple effect evaporator, Table 9 for quadruple effect evaporator and Table 10 for quintuple effect evaporator. In evaporator, water is evaporated by steam to reach concentrated juice. In evaporation and condensation process each temperature doesn't change. For the convenience, 0.1º temperature rise for cold streams and decrease in temperature 0.1º for hot streams (Zhang *et al*, 2015). Then, each heat capacity is obtained from each heat latent multiplied by 10 for evaporation or condensation. Individual thermal load in each stream has been calculated with heat capacity flowrate and temperature difference. Where heat capacity flowrate can be calculated by Eq (12).

$$CP = mc_p \tag{12}$$

Where, m is mass flowrate, kg/s and cp is spesific heat capacity, kJ/kg.K

Case Study

Algorithm for optimizing vapour bleeding has been illustrated in case study of raw sugar production at milling capacity 4000 TCD (ton cane per day) in various MEE formation. For calculation of hot and cold utility target a minimum temperature difference 6ºC is chosen to limit heat transfer. Properties of steam exhaust used from steam turbine under operationg condition of 2 kg/cm^2.a (T = 120ºC. λ = 525.7 kcal/kg), so that operating conditions for all MEE configuration can be seen in Table 1. Mass and heat balance have been carried out, hot and cold stream data can be obtained in Table 8, Table 9 and Table 10.

The next step after getting stream extraction is to make temperature interval. The actual temperature in each stream is replaced by shifted temperature.

Cold stream that needs to be heated have a shifted temperature above actual temperature. While hot stream that need to be cooled have a shifted temperature below actual temperature (Linnhoff *et al*., 1982) and (Kemp, 2007). Each interval will have a surplus or deficit of energy that depends on amount of heat capacity flowrate of each interval. To obtain energy of each interval can be calculated by following equation:

$$\Delta Hi = (T_i - T_{i+1})(\sum CP_H - \sum CP_C) \tag{13}$$

Where, Δhi is energy at interval i, kW. CPH is is heat capacity flowrate of hot stream and CPC is heat capacity flowrate of cold stream.

Table 8. Process stream data MEE triple effect evaporator

Stream	Name	Type	TA*		CP*	Q*
			In	Out		
1	Raw Juice	Cold	30	75	215	9675
2	Sulphited Juice	Cold	75	105	221	6630
3	Clear Juice	Cold	95	105	198	1980
4	Water EV 1	Cold	107.5	107.6	482862	48286
5	Water EV 2	Cold	90.5	90.6	277346	27735
6	Water EV 3	Cold	54.5	54.6	187814	18782
7	Water VP A	Cold	58	58.1	95344	9535
8	Water VP C	Cold	57.5	57.6	14545	1455
9	Water VP D	Cold	57.5	57.6	26546	2655
10	Air heater Sugar Drier	Cold	30	80	2	100
11	Wash water RVF	Cold	80	95	10	150
12	Imbibition water	Cold	80	95	83	98
13	Wash water HGF	Cold	80	105	83	108
14	Steam EV1	Hot	107	106.9	104	103.9
15	Steam EV2	Hot	89.6	89.5	86.6	86.5
16	Steam EV3	Hot	53	52.9	50	49.9
17	Steam VPA	Hot	53	52.9	50	49.9
18	Steam VPC	Hot	53	52.9	50	49.9
19	Steam VPD	Hot	53	52.9	50	49.9

*TA = Actual temperature in ºC
*CP = Spesific heat in KJ/Kg.ºC
*Q = Heat flux in kW

Table 9. Process stream data MEE quadruple effect evaporator

Stream	Name	Type	TA*		CP*	Q*
			In	Out		
1	Raw Juice	Cold	30	75	215	9675
2	Sulphited Juice	Cold	75	105	221	6630
3	Clear Juice	Cold	95	105	198	1980
4	Water EV 1	Cold	111	111.1	450517	45052
5	Water EV 2	Cold	100	100.1	225629	22563
6	Water EV 3	Cold	84.9	85	131182	13118
7	Water EV 4	Cold	55.00	55.10	131182	13118
8	Water VP A	Cold	58	58.1	95344	9535
9	Water VP C	Cold	57.5	57.6	14545	1455
10	Water VP D	Cold	57.5	57.6	26546	2655
11	Air heater Sugar Drier	Cold	30.00	80.00	2	100
12	Wash water RVF	Cold	80.00	95.00	10	150
13	Imbibition water	Cold	80.00	95.00	74	1110
14	Wash water HGF	Cold	80.00	105.00	0.01	0.25
15	Steam EV 1	Hot	111	110.9	450517	45052
16	Steam EV 2	Hot	100	99.9	225629	22563
17	Steam EV 3	Hot	84	83.9	131182	13118
18	Steam EV 4	Hot	53	52.9	131182	13118
19	Steam VPA	Hot	53	52.9	95344	9535
20	Steam VPC	Hot	53	52.9	14545	1456
21	Steam VPD	Hot	53	52.9	26546	2655

*TA = Actual temperature in ºC
*CP = Spesific heat in KJ/Kg.ºC
*Q = Heat flux in kW

Table 10. Process stream data MEE quintuple effect evaporator

Stream	Name	Type	TA*		CP*	Q*
			In	Out		
1	Raw Juice	Cold	30.00	75	215	9675
2	Sulphited Juice	Cold	75.00	105	221	6630
3	Clear Juice	Cold	95.00	105	198	1980
4	Water EV 1	Cold	112.9	113	413151	41315
5	Water EV 2	Cold	104.9	105	212478	21248
6	Water EV 3	Cold	94.9	95	138169	13817
7	Water EV 4	Cold	80.9	81	85748	8575
8	Water EV 5	Cold	55.9	56	85748	8575
9	Water VP A	Cold	57.9	58	95344	9535
10	Water VP C	Cold	57.9	58	14545	1455
11	Water VP D	Cold	57.9	58	26546	2655
12	Air heater Sugar Drier	Cold	30	80	2	100
13	Wash water RVF	Cold	80	95	10	150
14	Imbibition water	Cold	80	95	74	1110
15	Wash water HGF	Cold	80	105	0.01	0.25
16	Steam EV 1	Hot	113	112.9	413151	41315
17	Steam EV 2	Hot	105	104.9	212478	21248
18	Steam EV 3	Hot	94	93.9	138169	13817
19	Steam EV 4	Hot	80	79.9	85748	8575
20	Steam EV 5	Hot	53	52.9	85748	8575
21	Steam VPA	Hot	53	52.9	95344	9535
22	Steam VPC	Hot	53	52.9	14545	1456
23	Steam VPD	Hot	53	52.9	26546	2655

*TA = Actual temperature in ºC
*CP = Spesific heat in KJ/Kg.ºC
*Q = Heat flux in kW

After setting temperature interval, problem table, grand composite curve (GCC) and composite curve can be developed. From development of problem table, pinch point, hot utilities (QHmin), cold utilities (Qcmin) and maximum energy recovery can be identified explicitly.

Energy and amount external utilities can be seen in table 12 and table 13. To compare energy saving which the best configuration can be chosen table 15 showed performance value for each configuration such Steam on Cane (SOC), Steam Economy (SE) and Maximum Energy Recovery (MER).

Based on pinch analysis results, the optimization and retrofitting of the heat exchanger networks for each configuration have been performed. For design heat exchanger networks all matches between process stream must fullfill the CP criteria and number of stream criteria ($N_{HOTSTREAM}$ and $N_{COLDSTREAM}$), depicted in Figure 7.

The results of heat exchanger networks as follows:

1. Fig 11 shows that the heat exchanger networks for new integration works MEE triple effect evaporator that is converted into process flow diagram showed in Fig 12. Sugar plant 4000 TCD thermal system diagram new integration works for MEE triple effect evaporator.
2. Fig 15 shows that the heat exchanger networks for new integration works MEE quadruple effect evaporator that is converted into process flow diagram showed in Fig 16. Sugar plant 4000 TCD thermal system diagram new integration works for MEE quadruple effect evaporator.
3. Fig 19 shows heat exchanger networks for new integration works MEE quintuple effect evaporator that is converted into process flow diagram showed in Fig 20. Sugar plant 4000 TCD thermal system diagram new integration works for MEE quintuple effect evaporator.

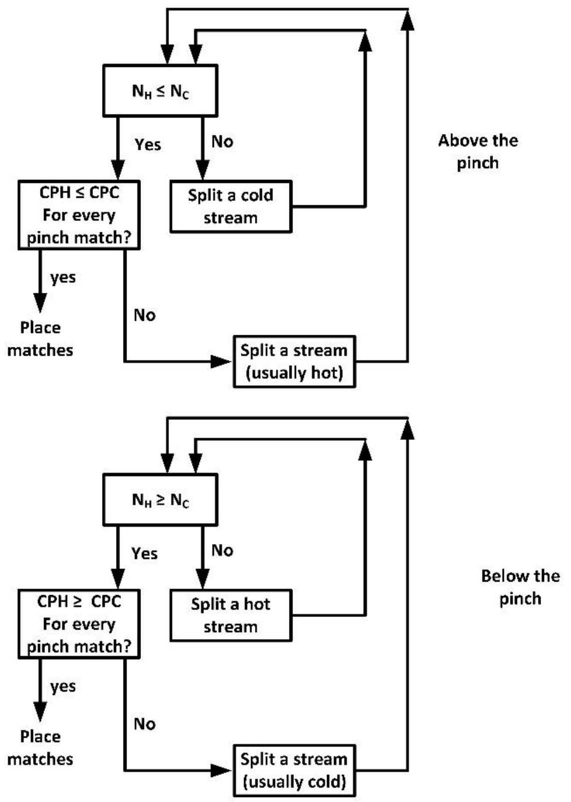

Fig 7. Algorithm for stream splitting at the pinch (B. Li *et al*, 2019)

Table 11. The summary of mass and heat balance

Parameter		Unit	Configuration: Existing Configuration	Quintuple effect evaporator	Quadruple effect evaporator	Triple effect evaporator
Steam pressure distribution	Exhaust steam	Kg/cm2.a	2	2	2	2
	EV 1	Kg/cm2.a	1.59	1.59	1.49	1.32
	EV 2	Kg/cm2.a	1.2	1.2	1.01	0.7
	EV 3	Kg/cm2.a	0.83	0.83	0.56	0.14
	EV 4	Kg/cm2.a	0.48	0.48	0.14	-
	EV 5	Kg/cm2.a	0.14	0.14	-	-
Steam temperature distribution	Exhaust steam	ºC	120	120	120	120
	EV 1	ºC	113	113	111	107
	EV 2	ºC	105	105	99	53
	EV 3	ºC	94	94	84	-
	EV 4	ºC	80	80	53	-
	EV 5	ºC	53	53	-	-
Steam flow distribution	Exhaust steam to EV 1	%cane	40.65	42.57	46.34	49.67
	Exhaust steam to JH III	%cane	2.14	-	0.37	1.14
	Exhaust steam to wash water RVF	%cane	0.06	-	-	-
	Exhaust steam to wash water HGF	%cane	-	-	-	0.0007
	Exhaust steamto JH II	%cane	-	-	0.41	1.28
	Auxiliary steam to sugar dryer	%cane	0.35	-	-	-
	Auxiliary steam to wash water HGF	%cane	0.19	-	-	-
	Vapour bleeding EV 1 to EV 2	%cane	21.07	20.47	21.56	26.11
	Vapour bleeding EV 1 to JH II (1)	%cane	-	-	-	5.39
	Vapour bleeding EV 1 to JH II (2)	%cane	3.38	3.22	-	-

Parameter		Unit	Configuration			
			Existing Configuration	Quintuple effect evaporator	Quadruple effect evaporator	Triple effect evaporator
Steam flow distribution	Vapour bleeding EV 1 to wash water RVF	%cane	-	0.13	0.13	0.13
	Vapour bleeding EV 1 to JH III	%cane	-	1.92	1.55	0.82
	Vapour bleeding EV 1 to wash water HGF	%cane	-	0.003	0.0026	0.0023
	Vapour bleeding EV 1 to sugar dryer	%cane	-	0.136	0.001	0.001
	Vapour bleeding EV 1 to Vacuum Pan	%cane	13.92	13.92	13.92	13.92
	Vapour bleeding EV 1 to imbibition water	%cane	-	0.98	0.98	0.98
	Vapour bleeding EV 2 to EV 3	%cane	13.3	13.1	12.32	16.96
	Vapour bleeding EV 2 to JH I/JH I (2)	%cane	4.35	4.35	9.14	9.14
	Vapour bleeding EV 2 to JH II (1)	%cane	3.35	3.35	-	-
	Vapour bleeding EV 3 to EV 4	%cane	9.02	7.99	12.32	-
	Vapour bleeding EV 3 to imbibition	%cane	1.01	-	-	-
	Vapour EV3 to condensor	%cane	-	-	-	16.96
	Vapour bleeding EV 3 to JH I (1)	%cane	5.37	5.3	-	-
	Vapour bleeding EV 4 to EV 5	%cane	8.00	7.99	-	-
	Vapour EV 4 to condensor	%cane	-	-	12.32	-
	Vapour EV 5 to condensor	%cane	8.00	7.99	-	-
Juice temperature distribution	Out EV 1	°C	112.93	112.92	110.94	107.32
	Out EV 2	°C	104.87	104.86	100.05	90.24
	Out EV 3	°C	94.91	94.90	84.83	54.8
	Out EV 4	°C	81.15	81.14	55.0	-
	Out EV 5	°C	55.3	55.29	-	-

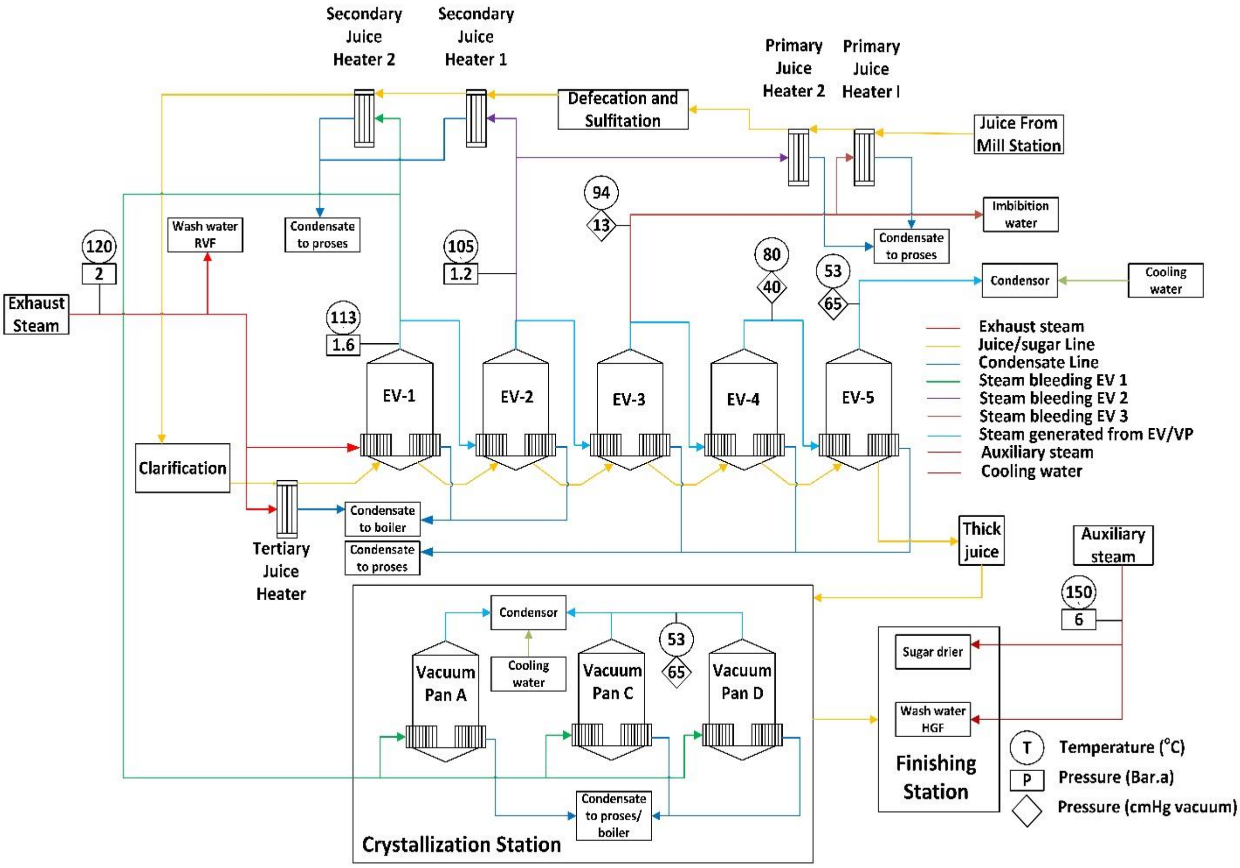

Figure 8. Sugar plant 4000 TCD thermal system diagram existing (MEE: Quintuple effect evaporator)

Table 12. External utilities heating duty for each configuration

Description		Flowrate (ton/hr)	Heating duty (kW)
Existing plant	Exhaust steam to EV 1	67.75	41393
	Exhaust steam to tertiary juice heater	3.39	2076.32
	Exhaust steam to wash water RVF	0.1	61.098
	Auxiliary steam to air heater sugar dryer	0.58	444.51
	Auxiliary steam to wash water HGF	0.32	245.24
Total		72.15	44220
Triple effect evaporator new works	Steam exhaust to evaporator effect 1	83.13	48286.2
	Steam exhaust to tertiary juice heater	1.9	792
	Steam exhaust to secondary juice heater	2.12	884
	Steam exhaust to wash water HGF	0.004	0.004
Total		86.81	50165
Quadruple effect evaporator new works	Steam exhaust to evaporator 1	77.24	45188.87
	Steam exhaust to tertiary juice heater	0.37	64
	Steam exhaust to sulphited juice heater	0.68	72
	Steam exhaust to wash water HGF	0.004	0.004
Total		78.53	45188.87
Quintuple effect evaporator new works	Steam exhaust to evaporator 1	70.96	41315.1
Total		70.96	41315.1

Table 13. External utilities cold duty for existing plant

Description		**Flowrate (ton/hr)**	**Cold duty (kW)**
Existing plant	Steam evaporator effect 5	13.34	8796.3
	Steam vacuum pan A	14.44	9518
	Steam vacuum pan C	2.2	1451
	Steam vacuum pan D	4	2650
Total		33.98	22415
Triple effect evaporator new works	Steam evaporator effect 3	28.44	18781
	Steam vacuum pan A	14.44	9534
	Steam vacuum pan C	2.2	1454
	Steam vacuum pan D	4	2654
Total		49.08	32316
Quadruple effect evaporator new works	Steam evaporator effect 4	20.53	13118
	Steam vacuum pan A	14.44	9534
	Steam vacuum pan C	2.2	1454
	Steam vacuum pan D	4	2654
Total		41.17	26762
Quintuple effect evaporator new works	Steam evaporator effect 5	13.32	8574
	Steam vacuum pan A	14.44	9534
	Steam vacuum pan C	2.2	1454
	Steam vacuum pan D	4	2654
Total		33.96	22204

Case 1 : MEE Triple Effect Evaporator

Analysis for MEE triple effect evaporator can be seen in grand composite curve (GCC) in Figure 9 and composite curve (CC) Figure 10. It is shown that pinch point at 104ºC, maximum energy recovery 77904.9 kW, hot duty at 50165 kW and cold duty at 30532.26 kW.

Vapour bleeding from evaporator 1 has higher temperature and pressure which allow it to be used as heater for other equipment. It can be seen in Figure 11 vapour bleeding evaporator 1 is used up to 10 users so that evaporation capacity and heating surface for evaporator effect 1 will be larger than evaporator effect 2 or evaporator effect 3. To maintain pressure and flowrate vapour bleeding in each evaporator requires heating surface according to evaporation capacity (Rein, 2007).

Heating surface each evaporator can be seen in Table 14, this configuration can match with heating surface existing condition (Table 3) which has higher value than minimum heating surface of this configuration.

To measure performance of MEE triple effect evaporator steam economy and steam on cane can be calculated. The definition of steam economy is the comparison of amount of evaporated water to amount of external steam used to evaporate the water (Chantasiriwan, 2017).

Table 14. Minimum heating surface required

Description		Heating surface (m2)
Triple effect evaporator new works	Evaporator effect 1	1149
	Evaporator effect 2	676
	Evaporator effect 3	454
Quadruple effect evaporator new works	Evaporator effect 1	1512
	Evaporator effect 2	794
	Evaporator effect 3	470
	Evaporator effect 4	496
Quintuple effect evaporator new works	Evaporator effect 1	1794
	Evaporator effect 2	971
	Evaporator effect 3	669
	Evaporator effect 4	437
	Evaporator effect 5	469

Table 15. Performance value for each configuration

Description	Steam On Cane (SOC)	Steam Economy (SE)	Maximum Energy Recovery (MER)
Existing plant (quintuple effect evaporator)	43.35	2.21	-
Triple effect evaporator new integration works	52.3	1.8	78155
Quadruple effect evaporator new integration works	47.12	1.94	81938
Quintuple effect evaporator new integration works	42.57	2.10	85225

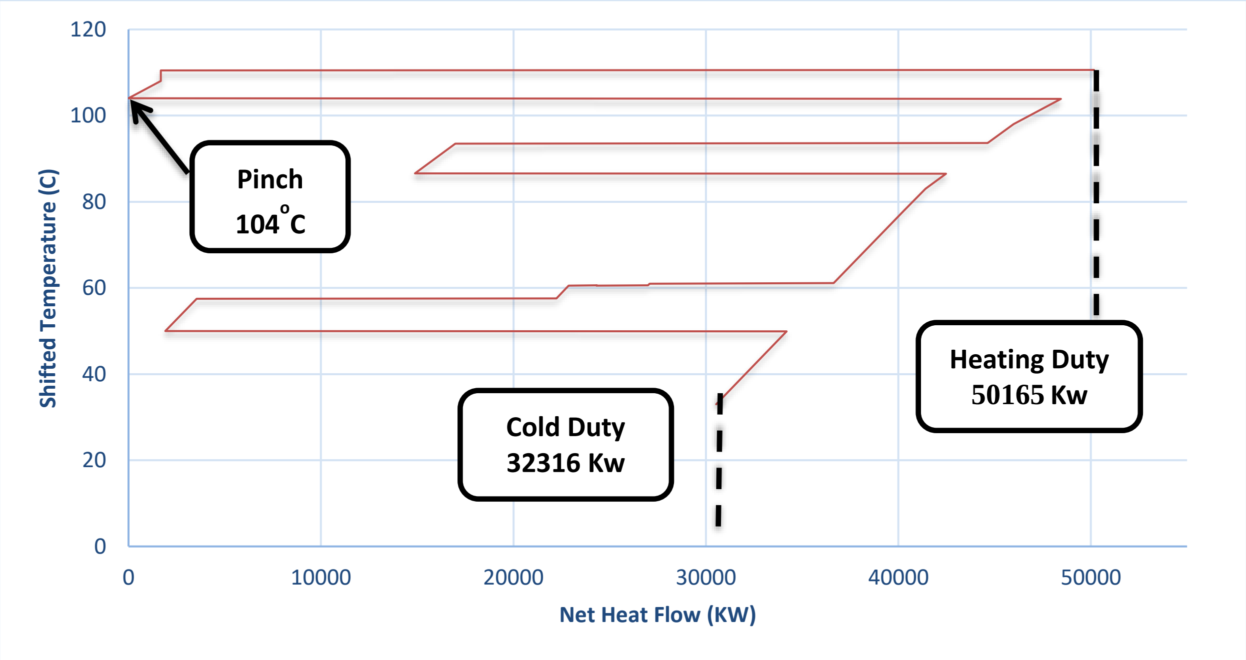

Figure 9. Grand Curve Composite MEE Triple Effect Evaporator

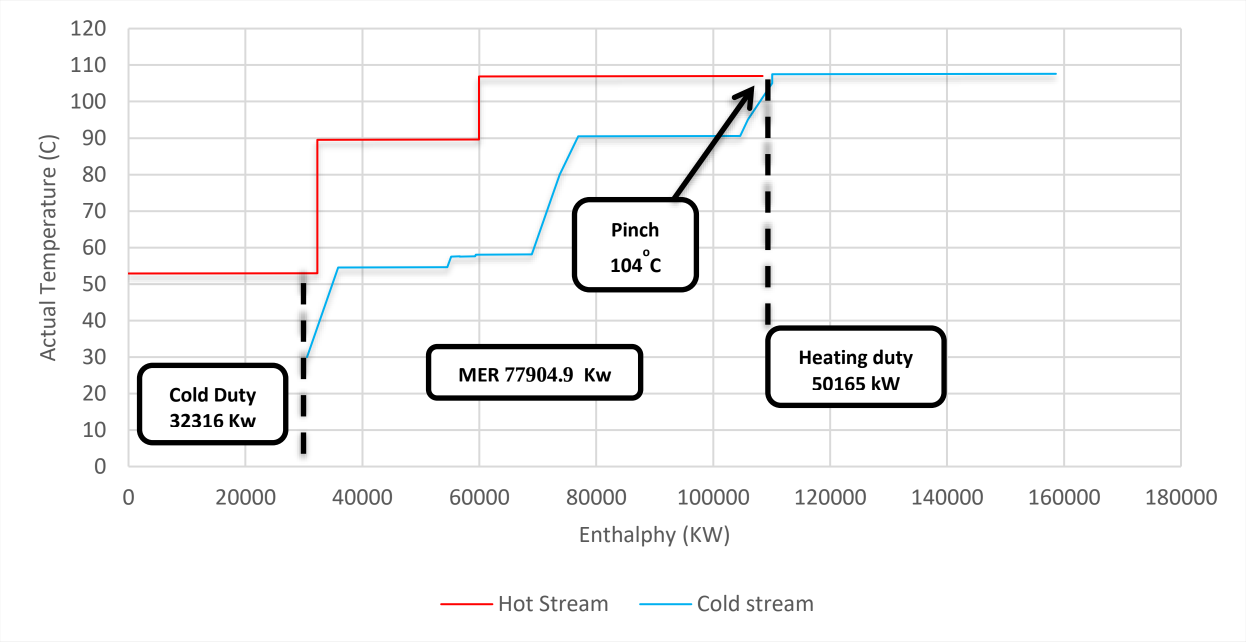

Figure 10. Composite Curve MEE Triple Effect Evaporator

From Table 15 it can be seen that steam economy of triple effect evaporator is 1.8. Triple effect evaporator has lowest value of SE, to produce thick juice with high concentration 64% brix, evaporation load in *n* effects evaporator will be divided by *n* effects. It says that evaporation load in evaporator effect 1 for others effect will be less than evaporation load in evaporator effect 1 for triple effect.

It can be concluded that heating duty demand (external utilities) of evaporator effect 1 for others effect is less than evaporator effect 1 for triple effect. So, this means, tripe effect evaporator has the lowest value steam economy. While steam on cane (SOC) is ratio of amount of high pressure steam demand from boiler to amount of sugar cane crushed (Singh *et al*, 1997). Table 15 shows that steam on cane from MEE triple effect evaporator is 52.3%.

It can be compared to external utilities for existing plan, heating duty demand for MEE triple effect evaporator is still larger than existing plant.

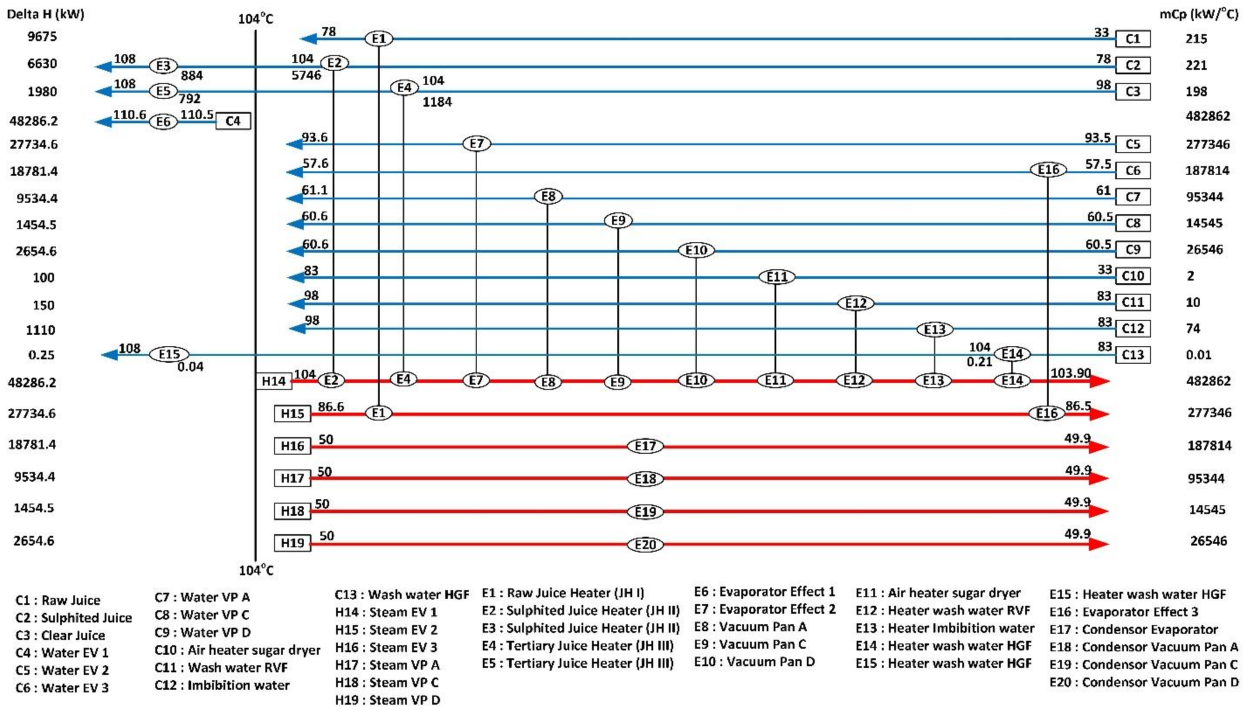

Figure 11. Heat Exchanger Network for new integration works MEE triple effect evaporator

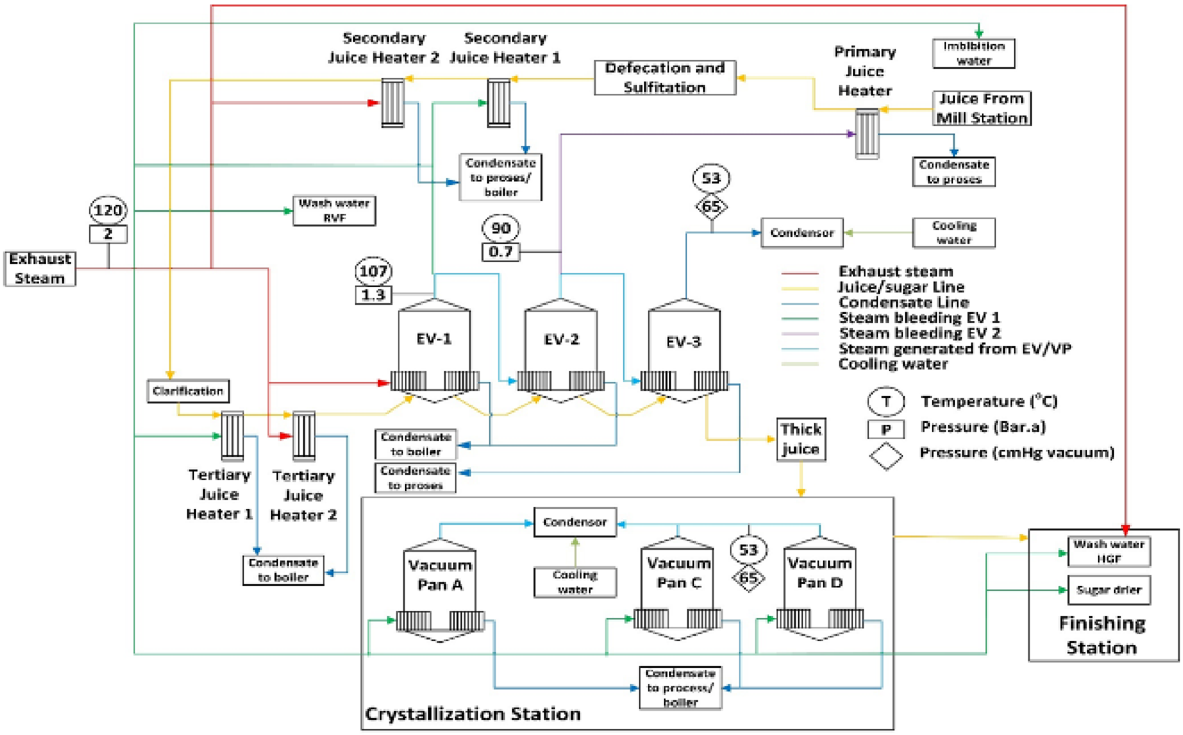

Figure 12. Sugar plant 4000 TCD thermal system diagram new integration works for MEE triple effect

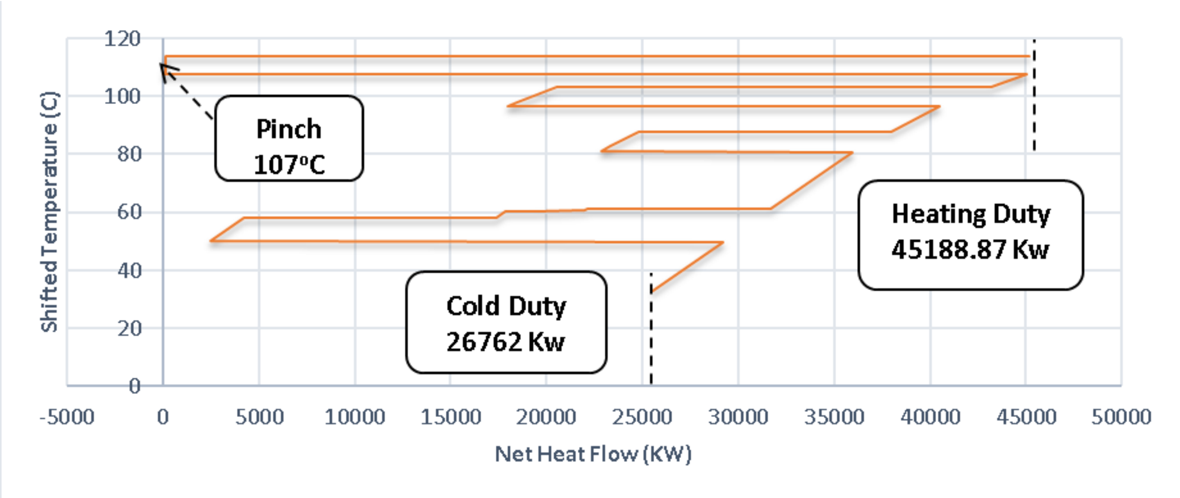

Figure 13. Grand Composite Curve MEE Quadruple Effect Evaporator

It is shown that, this formation consumes a lot of steam than others effect. In addition, the steam generated from evaporator 1 in condition of temperature 107°C and pressure 1.3 bar.a. This condition unable to heat secondary juice heater (105°C) and tertiary juice heater (105°C). Thus, the load of evaporator 1 is low so this means heat utility is required more so that Steam On Cane (SOC) for this configuration has the highest value.

From Figure 11 and Figure 12 it can be seen that auxiliary steam for sugar dryer and wash water HGF (P=5 bar, T=150°C) is no longer used in this formation. Also, steam heating on tertiary juice heater uses steam bleeding from evaporator effect 1 partially and continued with exhaust steam. But steam on cane (SOC) is still very high, because evaporation load on evaporator effect 1 still shows a higher value compared to existing plant (quintuple effect) and others effect.

Case 2 : MEE Quadruple Effect Evaporator

From pinch analysis, hot and cold utility for MEE quadruple effect evaporator has lower value than MEE triple effect evaporator. As previously mentioned, load evaporation to evaporator effect 1 for triple effect is larger than load evaporation effect 1 for quadruple effect. To achieve energy saving design for this formation, it can be seen in Figure 16 according to HEN (Heat Exchanger Network) (Figure 15).

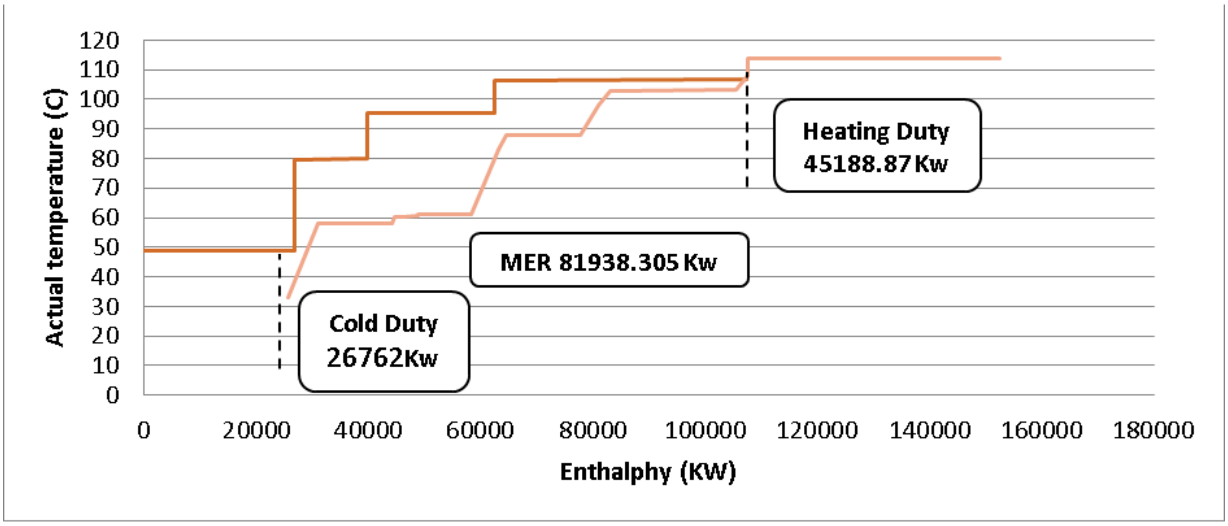

Figure 14. Composite Curve MEE Quadruple Effect Evaporator

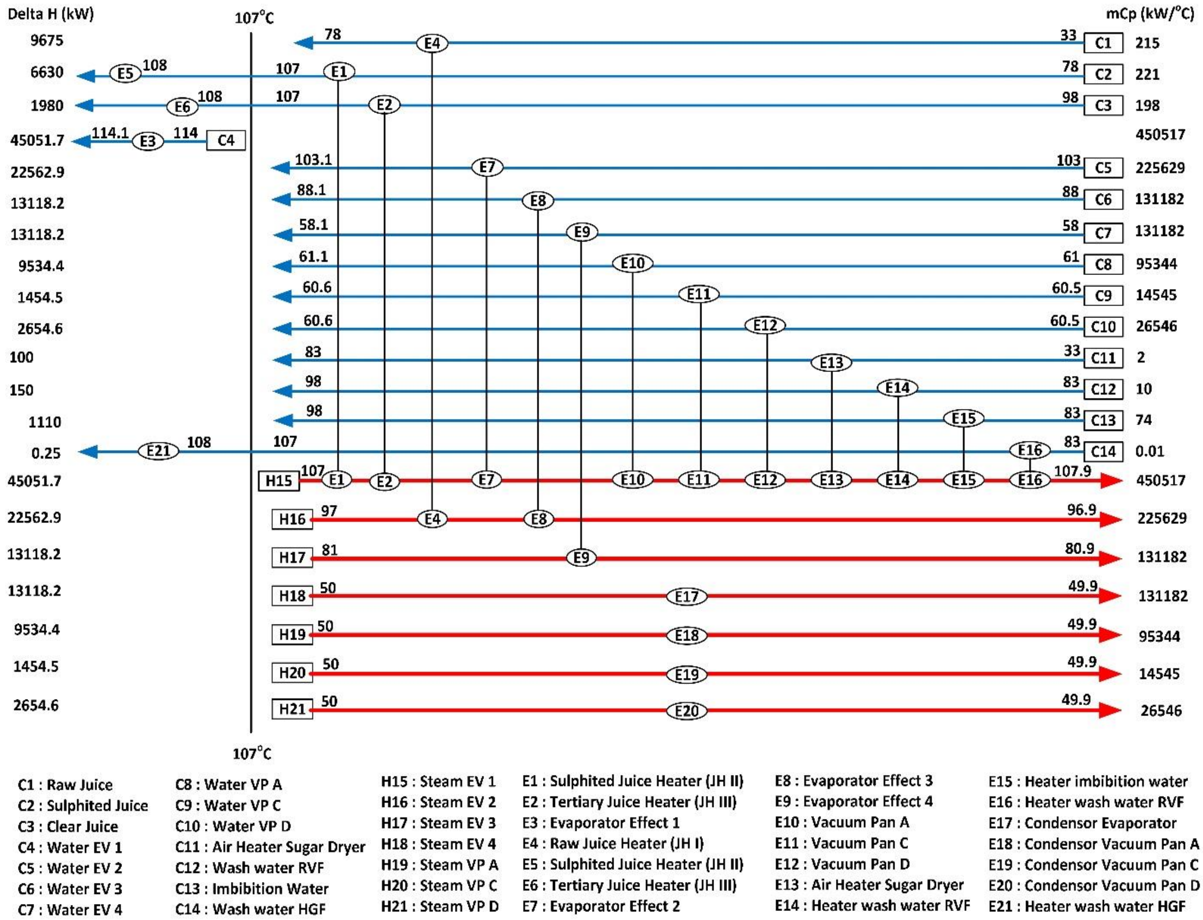

Figure 15. Heat Exchanger Network M EE Quadruple Effect Evaporator

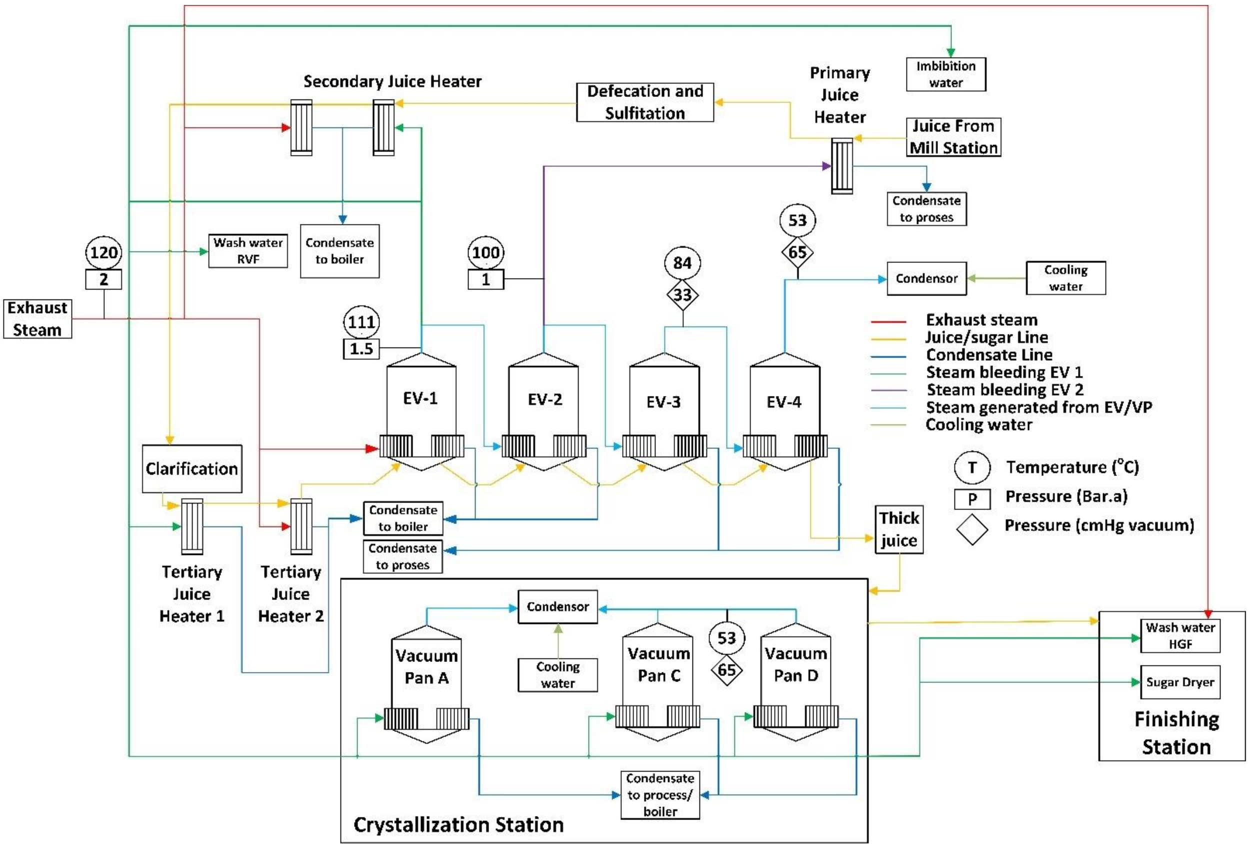

Figure 16. Sugar plant 4000 TCD thermal system diagram new integration works for MEE quadruple effect evaporator

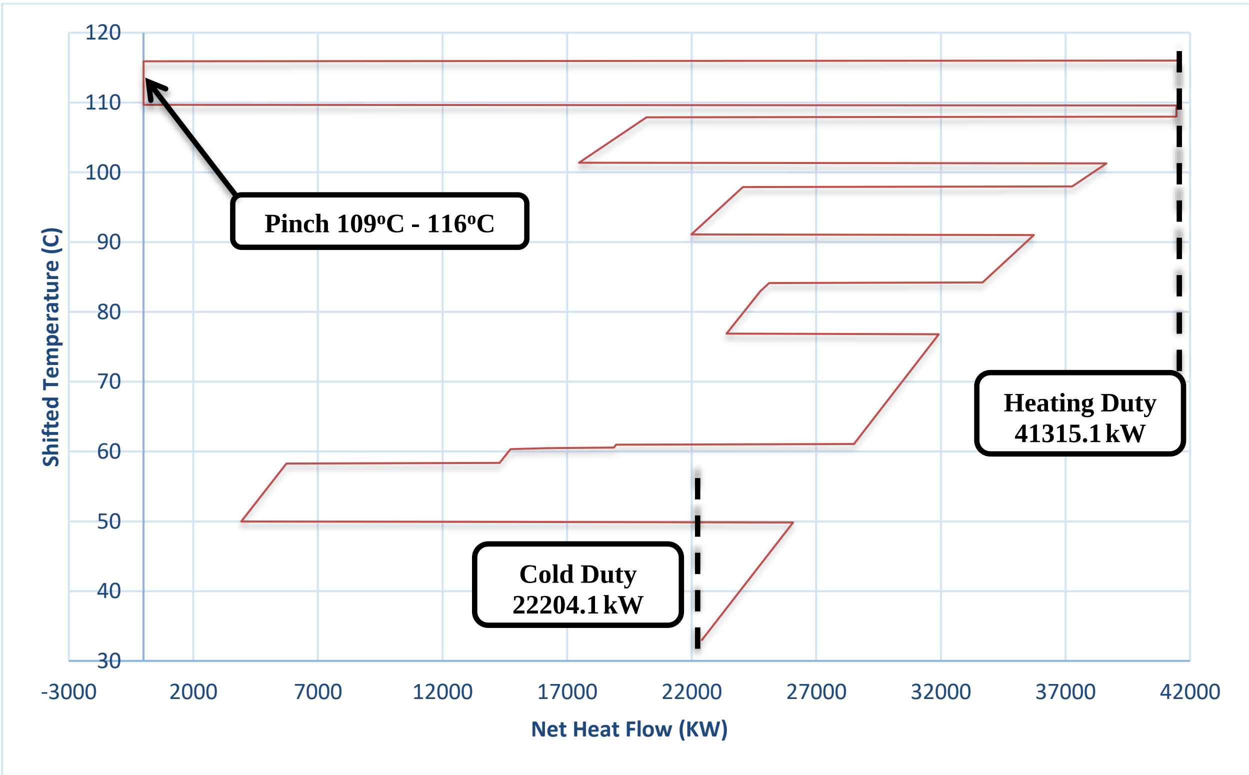

Figure 17. Grand Composite Curve MEE Quintuple Effect Evaporator

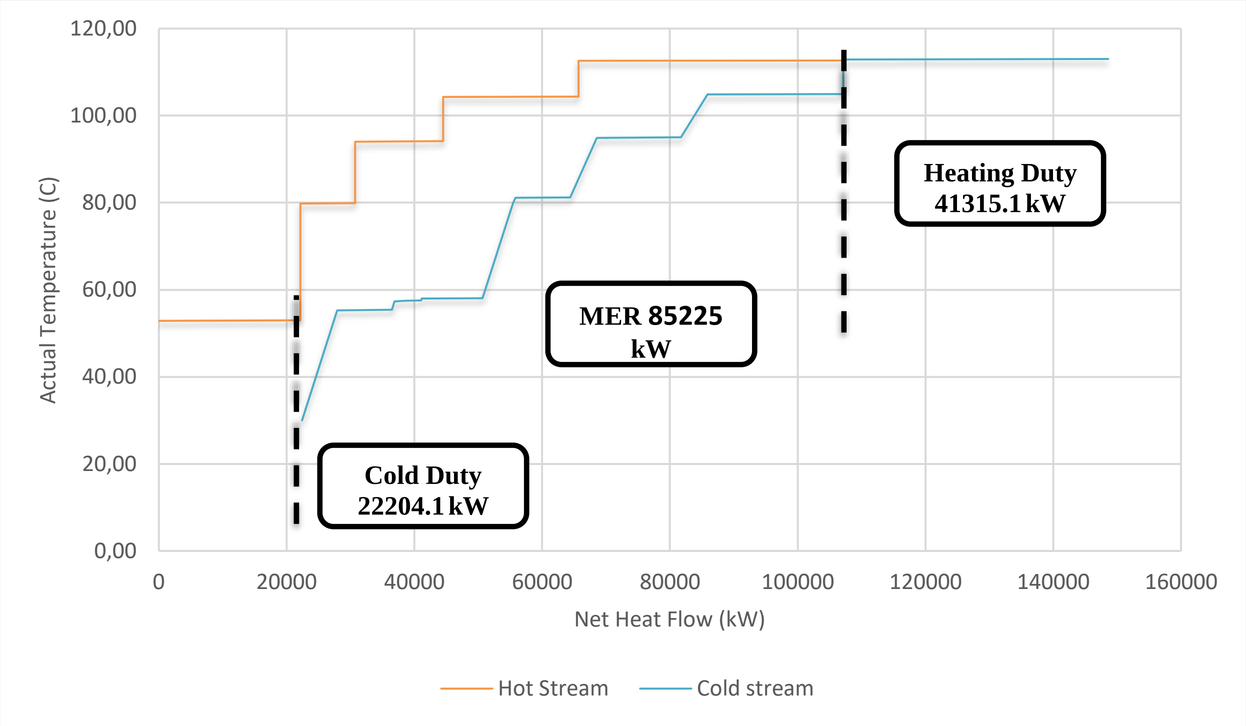

Figure 18. Composite Curve MEE Quintuple Effect Evaporator

In this formation has positive configuration, auxiliary steam for sugar dryer and wash water HGF (P=5 bar, T=150ºC) is no longer used in this formation. Also, steam heating on tertiary juice heater uses steam bleeding from evaporator effect 1 partially and continued with exhaust steam.

Performance of quadruple effect evaporator in SOC and SE can be calculated, the result is 47.12% and 1.94 (Table 15), respectively. Also Figure 12 and Figure 13 shows that cold duty and hot duty at 26762 kW and 45188.87 kW respectively.

The effect of evaporator configuration can affect to determine energy saving. Both cold and hot duty will be changed based on MEE configuration. The evaporation capacity in the last effect will determine the amount of cooling water that will be used as a condensation process in condensor. The evaporation capacity in the last effect is affected by amount of evaporation capacity in previous effect, the larger evaporation capacity in previous effect then the last effect will have low evaporation capacity. In steam bleeding process, effect 1 and effect 2 will supply heat to other heat exchanger. So, effect 1 and effect 2 should have a large evaporation capacity. This will result in a lower evaporation capacity in the last effect.

Case 3 : MEE Quintuple Effect Evaporator

Quintuple effect evaporator is often used in all sugar plant in Indonesia. in this formation, energy saving is superior compared to triple effect or quadruple effect. From the result of pinch analysis, Figure 17 and Figure 18 shows that the pinch point at temperature of 109 ºC -116 ºC and hot and cold utility targets have been calculated to be 41315 kW and 22204 kW respectively.

It can be seen from Figure 17 and Figure 18 maximum energy recovery (MER) for MEE quintuple effect evaporator is 85225 kW. While for SOC and SE quintuple effect evaporator has a value of 42.57% and 2.1 (table 15). To realize this configuration, heat exchanger network has been developed as shown in Figure 19 and Figure 20. It shows several improvements for realizing this energy saving configuration: 1) only evaporator effect 1 needs low pressure steam 2) tertiary juice heater is heated by steam bleeding evaporator effect 1 3) auxiliary steam for sugar dryer and wash water HGF (P=5 bar, T=150ºC) is no longer used in this formation.

Heating surface each evaporator can be seen in Table 14, this configuration can match with heating surface existing condition (Table 3) which has higher value than minimum heating surface of this configuration.

It can be seen in table 15 that Steam Economy (SE) for this configuration is lower than existing configuration. Existing configuration and this configuration have equal evaporation capacity, since the external utilities to heat evaporator effect 1 for existing capacity is lower than this configuration. Based on process flow diagram existing configuration fig 8 shows that vapour bleeding evaporator effect 1 has fewer users to be heated, it will lead evaporation capacity evaporator effect 1 less and caused steam economy for this configuration lower than existing configuration.

On Steam on Cane (SOC) side this configuration is superior than existing configuration. This configuration only 1 user needs hot external utility and other users that need hot external utilities are heated by vapour bleeding from evaporator. Existing configuration has additional external utilities for heating wash water HGF, tertiary juice heater and Sugar Dryer this will results high steam demand (hot external utilities).

Energy Saving Comparison

Performance of each configuration and Heat Exchanger Network (HEN) has been performed, however comparison energy saving of new integration works to existing configuration is not visible. In this paper will compare the maximum energy saving potential of the heat exchanger networks. It can be calculated by eq (13) and eq (14) (Zhang *et al*., 2015)

$$\delta_e = \frac{Q_H - Q_{Hmin}}{Q_H} x100\% \quad (14)$$

$$\delta_e = \frac{Q_C - Q_{Cmin}}{Q_C} x100\% \quad (15)$$

Where, QH is the existing configuration hot utility demand, kW; QHmin is new integration works required minimum hot utility, kW; QCmin is new integration works required minimum cold utility, kW.

Table 16. Energy saving compared to existing configuration

Description	δhot	δcold	Total
Triple effect evaporator new integration works	-13.44	-44.17	-57.6
Quadruple effect evaporator new integration works	-2.2	-19.40	-21.60
Quintuple effect evaporator new integration works	7	1	8

According to eq (13), eq (14) and table 16, the maximum energy saving potential of Heat Exchanger Network (HEN) is 8% for quintuple effect evaporator new integration works.

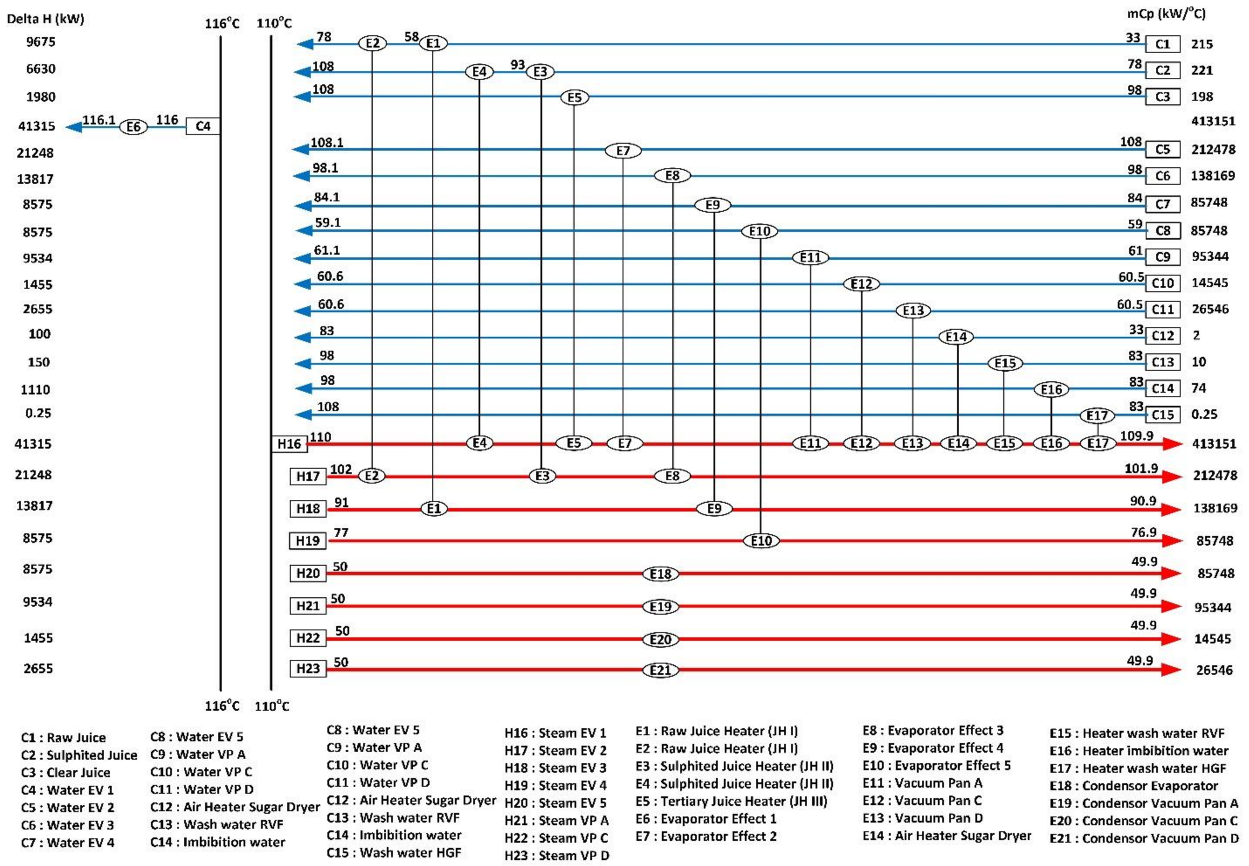

Figure 19. Heat Exchanger Network for new integration works MEE Quintuple Effect Evaporator

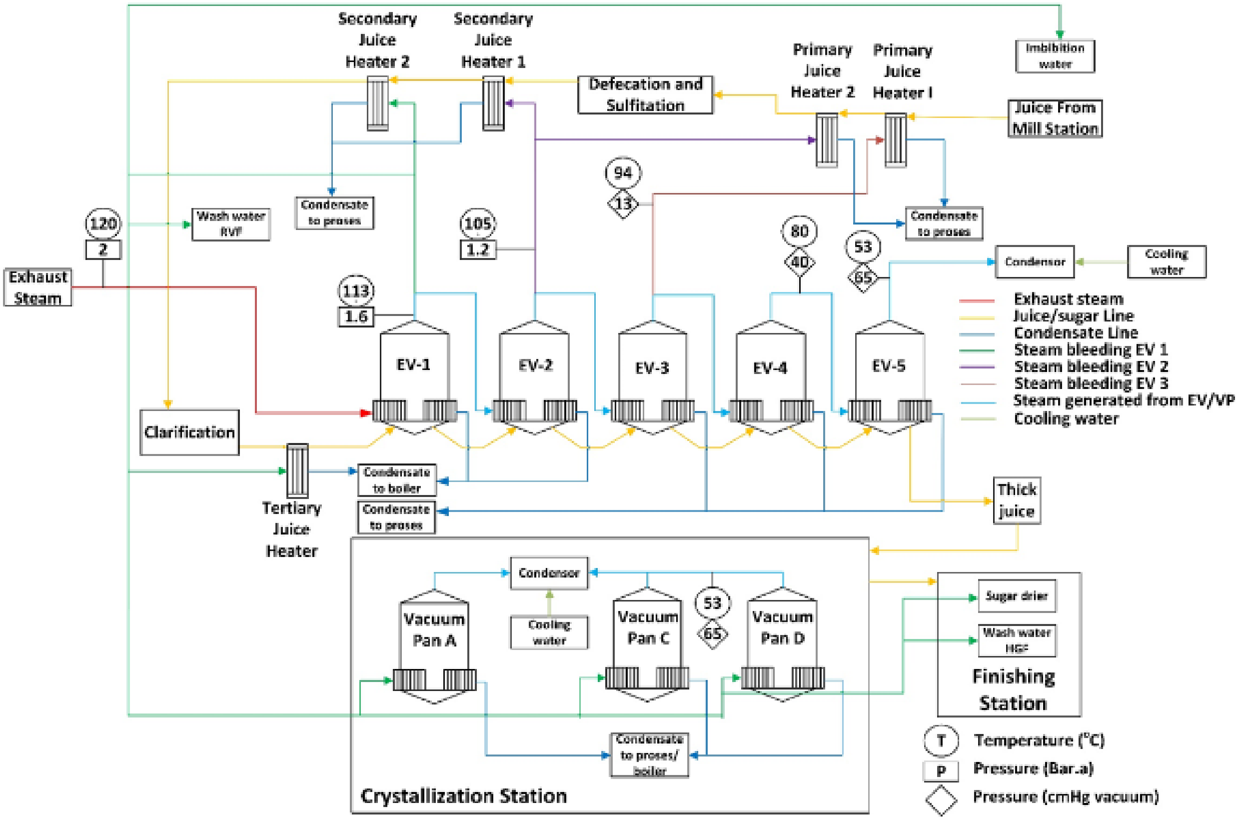

Figure 20. Sugar plant 4000 TCD thermal system diagram new integration works for MEE quintuple effect evaporator

CONCLUSION

Based on pinch analysis results, the optimal heat exchanger networks are proposed. To recover the waste heat further, the process integration of multiple effect evaporator is analyzed. Some final points can be made as follows.

In this paper new integration works for triple effect evaporator and new integration works for quadruple effect have been developed, the result for these integration works is maximum energy recovery for these new integration works have lower value than existing plant (quintuple effect evaporator).

Pinch analysis shows that the best configuration for this sugar plant is MEE quintuple effect evaporator with new integration works. It shows that pinch temperature in this paper for the best energy saving configuration is 109 °C-116 °C and the maximum energy saving potential is 8%. Based on minimum heating surface calculation, all effect evaporator in quintuple effect evaporator can be applied in evaporator that installed in sugar plant.

A new thermal system diagram is chosen to realize this integration works. New integration works for MEE quintuple effect evaporator propose several retrofiting those are only evaporator effect 1 needs low pressure steam (hot external utilities, tertiary juice heater is heated by steam bleeding evaporator effect 1, auxiliary steam for sugar dryer and wash water HGF (P=5 bar. G, T=150 °C) is no longer used in this formation.

ACKNOWLEDGEMENTS

This work is supported by “revitalization works of sugar plant mojo sragen PTPN IX Indonesia”

REFERENCES

Heluane, H., Blanco, A.M., Hernández, M.R. and Bandoni, J.A., (2012). Simultaneous re-design and scheduling of multiple effect evaporator systems. *Computers & operations research*, 39(5), pp.1173-1186.

Burke, B.J., (2014). Modelling and multi-objective optimization of a sugar mill based multi-effect evaporator set. *IFAC Proceedings Volumes*, *47*(3), pp.6716-6721.

Chantasiriwan, S. (2017). Investigation of Performance Improvement of the Evaporation Process in Raw Sugar Manufacturing by Increasing Heat Transfer Surfaces. *Chemical Engineering Communications*, *204*(5), pp. 599–606.

E. Hugot. (1986). *Handbook of Cane Sugar Engineering* (3rd ED). AMSTERDAM: Elsevier Ltd.

Gadalla, M.A., (2015). A novel graphical technique for Pinch Analysis applications: energy Targets and grassroots design. *Energy Conversion and Management*, *96*, pp.499-510.

Gautami, G. and Khanam, S., (2012). Selection of optimum configuration for multiple effect evaporator system. *Desalination*, *288*, pp.16-23.

Geankoplis, C. J. (1993). *Transport processes and unit operations Third Edition*. *The Chemical Engineering Journal*. New Jersey: Prentice Hall International Inc.

Higa, M., Freitas, A. J., Bannwart, A. C., and Zemp, R. J. (2009). Thermal integration of multiple effect evaporator in sugar plant. *Applied Thermal Engineering*, *29*(2–3), pp. 515–522.

Kemp, I. C. (2007). *Pinch Analysis and Process Integration Second Edition. A User Guide on Process Integration for the Efficient Use of Energy*. Oxford: Elsevier Ltd.

Kumar, D., Kumar, V., and Singh, V. P. (2013). Modeling and dynamic simulation of mixed feed multi-effect evaporators in paper industry. *Applied Mathematical Modelling*, *37*(1–2), pp. 384–397.

Lambert, C., Laulan, B., Decloux, M., Romdhana, H. and Courtois, F., (2018). Simulation of a sugar beet factory using a chemical engineering software (ProSimPlus®) to perform Pinch and exergy analysis. *Journal of Food Engineering*, 225, pp.1-11.

Li, B., Edy, Y., Castillo, C., and Chang, C. (2019). Chemical Engineering Research and Design An improved design method for retrofitting industrial heat exchanger networks based on Pinch Analysis. *Chemical Engineering Research and Design*, *148*, pp.260–270.

Li, Y., An, H., Li, W., Zhang, S., Jia, X., and Fu, L. (2018). Thermodynamic , energy consumption and economic analyses of the novel cogeneration heating system based on condensed waste heat recovery. *Energy Conversion and Management*, *177*(June), 671–681.

Linnhoff, B., Townsend, D. W., Boland, D., Hewitt, G. F., Guy, A. R., and Marsland, R. H. (1982). *A user guide on process integration for the efficient use of energy* (1st ed). United Kingdom: The Institution of Chemical Engineers, IchemE.

Rein, P. (2007). *Cane Sugar Engineering*. Berlin: Verlag Dr. Albert Bartens KG, 491.

Rosyid, O., Pudjo, and Diding. (2008). Studi Penghematan Energi pada Unit Ketel Uap di Pabrik Gula. *Jurnal Sains Dan Teknologi Indonesia*, *10(3)*, pp.171–176.

Safder, U., Ifaei, P., and Yoo, C. (2019). Multi-scale smart management of integrated energy systems , Part 2 : Weighted multi-objective optimization , multi-criteria decision making , and multi-scale management (3M) methodology. *Energy Conversion and Management*, *198*(April), pp.111830.

Safder, U., Ifaei, P., and Yoo, C. (2020). A novel approach for optimal energy recovery using pressure retarded osmosis technology : Chemical exergy pinch analysis – Case study in a sugar mill plant. *Energy Conversion and Management*, *213*, pp.112810.

Singh, I., Riley, R., and Seillier, D. (1997). Using pinch Technology to Optimise Evapoorator and Vapour Configuration at Malelane Mill. *Proceedings of the South African Sugar Technological Association, 71*, pp.207–216.

Umar, B. N., Ahmed, E. U., and Ahmed, S. I. (2017). Energy Integration of Sugar Production Plant Using Pinch Analysis : A Case Study of Savanah Sugar Company Yola , Nigeria. *Pelagia Research Library:Advances in Applied Science Research*, *8*(2), pp.20–29.

Zhang, K., Liu, Z., Huang, S., and Li, Y. (2015). Process integration analysis and improved options for an MEA CO2 capture system based on the pinch analysis. *Applied Thermal Engineering*, *85*, pp.214–224.