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Research Article

Pinch-Exergy Approach to Enhance Sulphitation Process Efficiency in Sugar Manufacturing

Pendekatan Pinch-Eksergi sebagai Peningkatan Efisiensi Proses Sulfitasi di Pabrik Gula

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Abstract

This study aimed to enhance the thermal efficiency of the sulphitation process in the boiling house of sugar plants using a combined approach of pinch and exergy analyses. Pinch analysis is a reliable method for optimizing the design of energy recovery systems. However, the primary limitations arise from its exclusive focus on heat transfer processes. On the other hand, exergy balance provides valuable insight into the consumption of supplied exergy by individual process units, serving as a quantitative measure of inefficiency. The boiling house was evaluated and modified using pinch-exergy analysis with Sulphitation Process capacity production of 8000 TCD. The results showed a potential reduction in exergy destruction by approximately 10.25 MW. The optimization effort led to reductions of 18.18 and 14.70% in the use of hot and cold external utility, respectively.

Keywords: boiling house; exergy analysis; heat exchanger network; pinch analysis; process integration; sugar plant

Abstrak

Pada penelitian ini, kombinasi analisis pinch dan eksergi diaplikasikan pada proses Sulfitasi di unit boiling house pabrik gula sebagai peningkatan efisiensi energi. Analisis pinch dikembangkan sebagai alat perhitungan yang digunakan untuk optimasi desain dengan menghemat energi. Namun, salah satu batasan pinch analysis adalah teknik yang digunakan sebatas penghematan energi saja yaitu perpindahan panas. Neraca eksergi digunakan pada sistem untuk mengetahui seberapa besar eksergi yang dipindahkan ke sistem yang telah terkonsumsi oleh unit proses. Kehilangan eksergi merupakan menginformasi seberapa besar proses yang inefisien. Tujuan dari penelitian ini adalah evaluasi dan modifikasi jaringan panas dengan menggunakan metode pinch-exergy pada proses sulfitasi dengan kapasitas giling 8000 TCD. Evaluasi dan modifikasi jaringan penukar panas menghasilkan pengurangan nilai kehilangan eksergi sebesar 10,25 MW. Terlebih lagi, jumlah utilitas panas eksternal dan jumlah utilitas dingin eksternal dapat dikurangi sebesar 18,18% dan 14,70% secara berturut-turut.

***Kata kunci**: analisis eksergi; analisis pinch; boiling house; jaringan penukar panas; pabrik gula; proses integrasi*

1. Introduction

The focus of this investigation centers on sugar plants, where the predominant method used for converting sugarcane into sugar is the sulphitation process. A significant component of the sulphitation process is the Multiple Effect Evaporation (MEE) system, which needs a large amount of heat. However, the integration of MEE includes using the steam generated from an effect in other facilities [1]. Considering the amount of energy in the sugar factory, some efforts are made to minimize its requirements. Energy optimization can be performed using several methods, including exergy and pinch analyses [2].

Pinch analysis has proven effective in optimizing energy in various industries by constructing a better heat exchanger network to reduce the utility of heating and cooling media [3]. This analysis offers the benefit of extracting information through visual aids such as composite curves, grand composite curves, and grid diagrams [4]. The desired energy target is determined prior to constructing the heat exchanger network [5]. Several studies have used pinch analysis in industrial energy management. For instance, Westphalen et al investigated a triple-effect evaporator system in a sugar factory, showing a potential reduction in heating utility consumption by up to 23% [6]. Singh et.al [7] applied pinch analysis to optimize energy usage in the Malelane Mill sugar factory, achieving a decrease in steam on cane (SOC) from 67% to 56.2% - 56.8% with a payback period of 1.11 - 1.19 years. Additionally, Riadi et.al [8] reported a 30% potential energy savings in MEE using Low-Pressure Steam (LPS) at 0.9 – 1.1 kg/cm^2.G.

The application of pinch technology to increase energy efficiency has shown satisfactory results. A detailed examination focuses on energy optimization through a thermodynamic analysis based on the exergy concept. Exergy analysis is a method used for energy optimization and evaluation within a system. Applying exergy balance across the entire plant provides insights into the available potential energy and the extent to which exergy supplied to the system has been used by the various process units [9]. Loss of exergy or irreversibility provides a general quantitative measure of process inefficiency [10]. Individual analyses can be conducted to pinpoint the specific unit responsible for the highest exergy loss contribution [11] and show the optimization potential of the system [12]. Particularly in systems using a workload, such as refrigeration [13], the primary aim is to determine the minimum work required to achieve a specific desired outcome [14]. The design of the Heat Exchanger Network (HEN) for the sulphitation process is presented in Figure 1, while the exergetic efficiency of the boiling sulphitation process component for base case design is shown in Table 1. Pinch analysis of the process has shown energy inefficiency in the current configuration of the HEN design.

In this study, the initial step entails describing the operation of a boiling house in a typical sulphitation process. Subsequently, exergy equations were formulated for each component within the boiling house process for the base case design. Exergy analysis was conducted to compute both exergetic efficiency and destruction for each individual component within the boiling house process for the base case design. The combined use of exergy destruction and exergetic efficiency serve as effective tools for assessing energy performance [15], facilitating the identification of sources within the system requiring optimization. Additionally, a method was outlined for determining the minimum heat requirement for a boiling house. The objective of this study includes providing suggestions for decreasing SOC while discussing the reason for deviation from the reversible process. Both pinch and exergy analysis methods were used for improving exergetic efficiency.

The process flow diagram of the boiling house sulphitation process in a sugar plant, operating at a capacity of 8000 TCD is shown in Figure 1. In this study, raw juice from a mill station was heated up to 75°C by 2 primary heaters (JH1-1 and JH1-2) for the defecation and sulphitation process, using vapor bled from 3rd and 2nd effect evaporators, respectively. Subsequently, the temperature of sulphitated juice was raised to 105°C using two secondary heaters (JH2-1 and JH2-2). This heating was accomplished through vapor extracted from the 2nd and the 1st effect evaporators, respectively, before transferring the juice to the clarifier. Prior to being introduced into the 1st effect evaporator, the clear juice (with a concentration of 11.9% brix) from the clarifier was raised to a temperature of 105°C. This process was achieved through vapor extracted from the 1st effect evaporator, facilitated by the tertiary heater (JH3). MEE (EV-1, EV-2, EV3, EV-4, and EV-5) were operated at low-pressure steam 1 kg/cm^2.G, with the 5th effect evaporator operating at 0.14 kg/cm^2.a. Thick juice as a product should have 64 %brix being fed to crystallization station. In this station, all Vacuum Pans (VPA, VPC, and VPD) were heated by 1st effect evaporator and at vacuum condition of 0.14 kg/cm^2.a. Massecuite A, Massecuite C, and Massecuite D were the products obtained from Vacuum Pan A, C, and D, respectively, with approximate concentrations of 94%, 96%, and 98%, correspondingly.

2. Research Methods

The commercial simulator Aspen Plus version 11 from Aspen Technology was used to generate simulated data. The selected fluid package for process simulation was NRTL. Thermodynamics properties such as water activity, osmotic coefficient, vapor pressure, boiling point temperature, freezing point, and solubility were described in 3 binaries systems, namely D-fructose, water, and sucrose [16] [17].

In the Aspen Plus model of the sulphitation process within the boiling house, D-fructose was used as a representation for all non-sucrose sugar, while sucrose specifically denotes sucrose sugar. In this study, exergy calculation and analysis were conducted in Aspen Plus and Excel. It is important to note that exergy analysis should be preceded by mass and energy balances of the system.

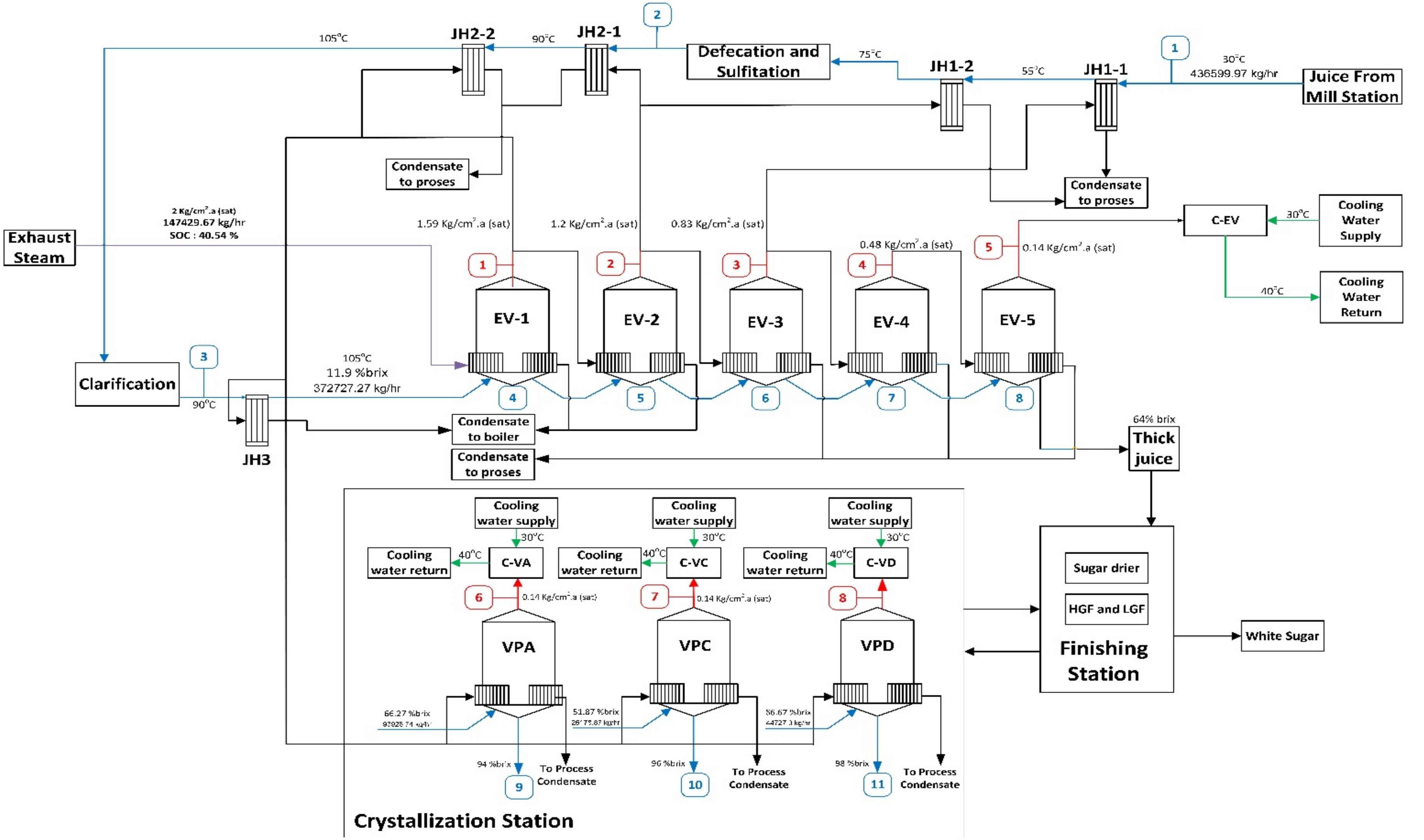

Figure 1. Boiling house sulphitation process in sugar plant base case design

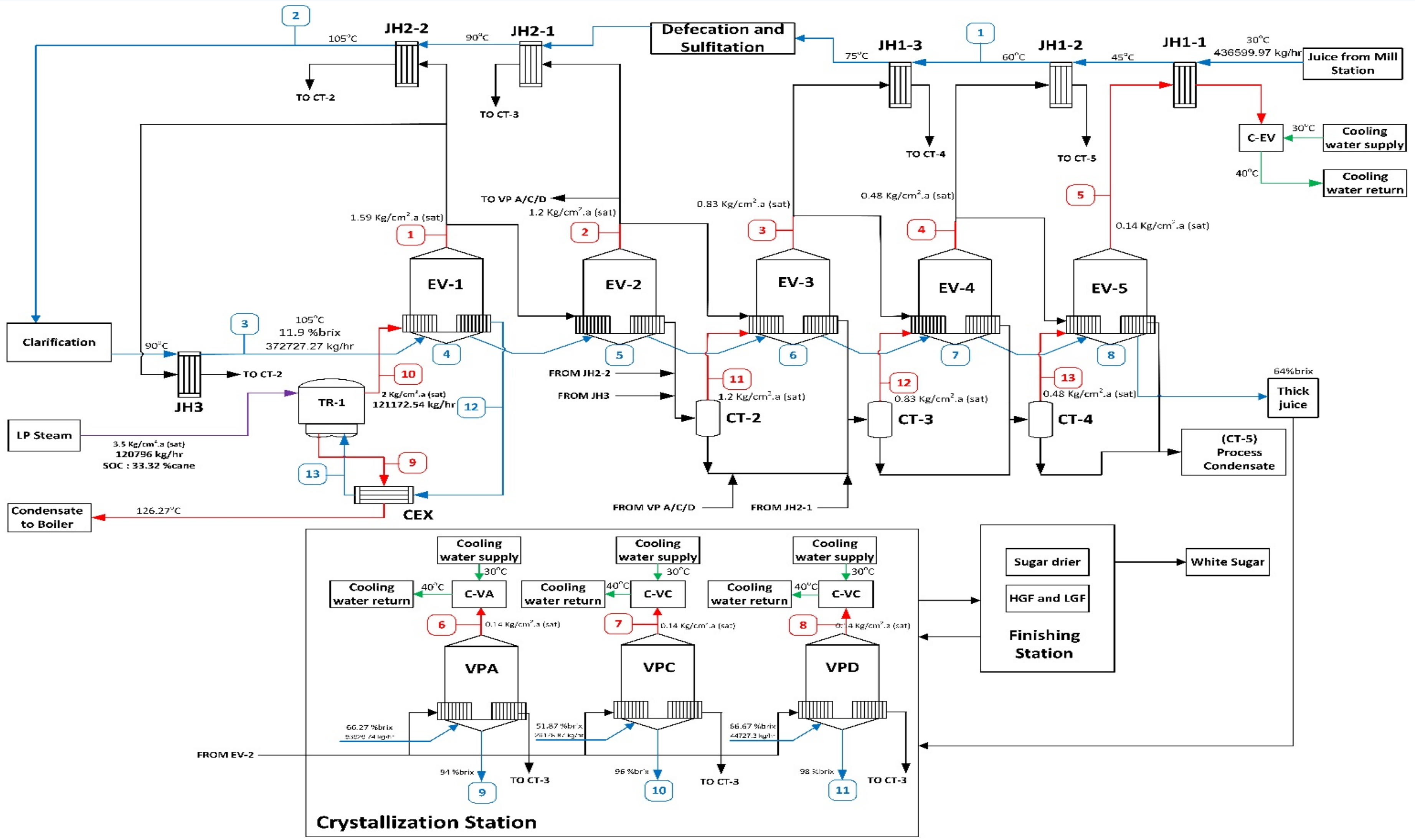

Figure 2. Optimized boiling house sulphitation process in sugar plant

Table 1. Exergetic efficiency of boiling house sulphitation process components for base case design

HE	Stream		T (°C)		Q (kJ/hr)	m (kg/hr)	H (kJ/kg)		S (kJ/kg.K)		Ex (kJ/hr)	η
			In	Out			In	Out	In	Out		
JH1-1	Shell (h)	Bleed EV3	95.70	94.52	40955782	18000	13288.63	15563.95	1.97	8.16	5395020.98	86.83
	Tube (c)	Raw Juice	30.00	55.01		436600	14138.83	14045.02	8.21	7.91		
JH1-2	Shell (h)	Bleed EV-2	105.69	104.83	33709284	15000	3270.22	15517.50	2.09	8.04	2963629.32	91.21
	Tube (c)	Raw Juice	55.01	75.01		436600	14045.02	13967.81	7.91	7.69		
JH2-1	Shell (h)	Bleed EV-2	105.69	104.83	26068513	11600	13270.22	15517.50	2.09	8.04	1053870.37	95.96
	Tube (c)	Sulphited Juice	75.01	90.08		436600	13967.81	13908.10	7.69	7.52		
JH2-2	Shell (h)	Bleed EV-1	113.75	113.16	26576780	11950	13255.34	15479.34	2.18	7.94	511038.65	98.08
	Tube (c)	Sulphited Juice	90.08	105.04		436600	13908.10	13847.23	7.52	7.36		
JH3	Shell (h)	Bleed EV-1	113.75	113.16	22707023	10210	13255.34	15479.34	2.18	7.94	437443.84	98.07
	Tube (c)	Clear Juice	90.06	105.01		372727	13954.38	13893.46	7.55	7.38		
EV1	Shell (h)	LPS	120.27	120.27	324948733	147500	13243.92	15446.96	2.26	7.86	4136360.39	98.73
	Tube (c)	EV1 Juice	105.01	113.75		372727	13893.46	13021.64	7.38	5.13		
EV2	Shell (h)	Bleed EV1	113.75	113.16	131150628	58970	13255.34	15479.34	2.18	7.94	2038603.67	98.45
	Tube (c)	EV2 Juice	105.40	105.69		232546	12880.77	12316.79	6.90	5.42		
EV3	Shell (h)	Bleed EV2	105.69	104.83	78900049	35109	13270.22	15517.50	2.09	8.04	1573943.28	98.01
	Tube (c)	EV3 Juice	95.34	95.70		170837	11972.40	11510.56	6.61	5.36		
EV4	Shell (h)	Bleed EV3	105.69	104.83	44201670	19426	13288.63	15563.95	1.97	8.16	1303214.59	97.05
	Tube (c)	EV4 Juice	95.34	95.70		133411	11011.75	10680.43	6.30	5.37		
EV5	Shell (h)	Bleed EV4	81.82	80.33	50267042	21738	13314.43	15626.80	1.79	8.34	3381584.00	93.27
	Tube (c)	EV5 Juice	53.87	54.72		111672	10167.69	9717.56	6.06	4.68		
VPA	Shell (h)	Bleed EV1	113.75	113.16	66497551	29900	13255.34	15479.34	2.18	7.94	8612196.69	87.05
	Tube (c)	VPA syrup	54.94	67.10		93926	8479.05	7771.07	5.54	3.40		
VPC	Shell (h)	Bleed EV1	113.75	113.16	29023179	13050	13255.34	15479.34	2.18	7.94	3832074.14	86.80
	Tube (c)	VPC syrup	53.98	73.53		26178	9781.85	8673.20	5.96	2.60		
VPD	Shell (h)	Bleed EV1	113.75	113.16	35806374	16100	13255.34	15479.34	2.18	7.94	4372845.70	87.79
	Tube (c)	VPD syrup	55.31	87.21		44727	7742.63	6942.08	4.94	2.54		
C-EV	Shell (h)	vapor EV5	54.72	52.55	59125099	24827	13364.61	15746.02	1.37	8.69	2882715.46	95.12
	Tube (c)	Cooling water	30.00	39.81		1450000	15843.68	15802.90	8.99	8.86		
C-VA	Shell (h)	vapor VPA	67.10	52.55	66661914	27765	13317.98	15718.91	1.30	8.67	3266870.56	95.10
	Tube (c)	Cooling water	30.00	39.83		1630000	15843.68	15802.78	8.99	8.85		
C-VC	Shell (h)	vapor VPC	73.53	52.56	29120995	12098	13267.43	15674.39	1.26	8.65	1436289.52	95.07
	Tube (c)	Cooling water	30.00	39.86		710000	15843.68	15802.66	8.99	8.85		
C-VD	Shell (h)	vapor VPD	87.21	52.58	35049029	14539	13101.94	15512.62	1.17	8.56	1774459.14	94.94
	Tube (c)	Cooling water	30.00	39.80		860000	15843.68	15802.92	8.99	8.86		

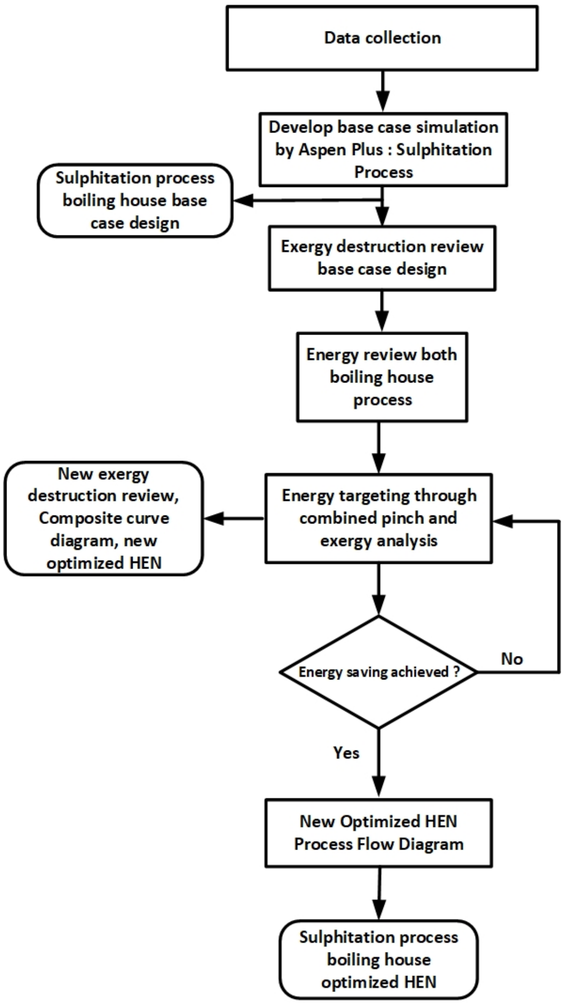

Figure 3. Flowchart of works methodology

Aspen stream results were exported to Excel. Energy optimization of HEN was conducted with the help of Aspen Energy Analyzer v.11. Figure 3 provides a full description of the study approach. The process commenced by collecting the required data to create a simulation of the base case design for a boiling house in a sugar plant. This data comprised specifications for the juice and syrup inputs and outputs, flow details for the shell and tube sides of all heat exchangers (HE), and operating conditions. The next step included the computation of exergetic efficiency from the base case design of the HEN. These exergetic efficiency calculations were conducted to determine the extent of exergy destruction before any optimization.

The basic concept revolves around the application of the first law of thermodynamics. The law states that while energy cannot be created or destroyed, it can change forms. This principle finds application in heat exchangers, devices designed to transfer heat from a higher to lower temperature fluid. In this process, the hot stream serves as the heat source, elevating the temperature of the cold stream. The complete transfer of energy from the hot to cold stream is impeded by the second law of thermodynamics. According to the law, entropy (ΔS) consistently increases ($\Delta S > 0$). Consequently, a portion of the energy is inevitably lost, leading to an increase in entropy [18]. This rise is a fundamental characteristic defining irreversibility in the thermodynamic process. The concept of exergy represents the maximum useful work obtainable from a system [19]. The loss of work during the process is termed lost work, denoted as W_{lost}. It is defined as the difference between the ideal work (W_ideal) achievable for the same change of state and the actual work (W_s) performed during the change of state [19]. The system can be expressed as Equation (1).

In terms of rates, Equation (1) can be transformed into Equation (2). The actual work was calculated using the energy balance, Equation (3), while the ideal work rate was obtained using Equation (4). Substituting equations 3 and 4 into 2 produced Equation (5). For single surroundings temperature (T_σ), the steady-state entropy balance was expressed by Equation (6), and multiplying by T_σ, yielded Equation (7). Since the right side of Equation (7) and (5) were identical, the equation was simplified as given by Equation (8).

The lost work from Equation (5) can be transformed into (9). After obtaining the W_{lost} value, the calculation for $\%W_{lost}$ can be expressed in Equation (10), which is the proportion of the W_{lost} value to heat exchanger heating load.

$$W_{lost} \equiv W_s - W_{ideal} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

$$\dot{W}_{lost} \equiv \dot{W}_s - \dot{W}_{ideal} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

$$\dot{W}_s = \Delta\left[\left(H + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} - \dot{Q} \quad \ldots\ldots\ldots\ldots \text{(3)}$$

$$\dot{W}_{ideal} = \Delta\left[\left(H + \frac{1}{2}u^2 + zg\right)\dot{m}\right]_{fs} - T_\sigma \Delta(S\dot{m})_{fs} \ldots \text{(4)}$$

$$\dot{W}_{lost} = T_\sigma \Delta(S\dot{m})_{fs} - \dot{Q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

$$\dot{S}_G = \Delta(S\dot{m})_{fs} - \frac{\dot{Q}}{T_\sigma} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

$$T_\sigma \dot{S}_G = T_\sigma \Delta(S\dot{m})_{fs} - \dot{Q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(7)}$$

$$\dot{W}_{lost} = T_\sigma \dot{S}_G \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

$$\dot{W}_{lost} = T_\sigma\{\dot{m}_H(\Delta S)_H + \dot{m}_C(\Delta S)_C\} \quad \ldots\ldots\ldots\ldots \text{(9)}$$

$$\%W_{lost} = \frac{W_{lost}}{\dot{Q}} x100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

4. Results and Discussion

Exergy destruction and efficiency were provided along with the schematic of the component. Furthermore, the flow streams based on the states in Figure 1 are shown in Table 1. An exergy analysis of the boiling house sulphitation process in a sugar plant was conducted in the present study to evaluate the amount of exergy destruction and efficiency in each component. Across all components of the boiling house, a discernible level of irreversibility was observed. According to exergy analysis, heat exchangers, namely JH1-1 (86.83%), VPA (87.05%), VPC (86.80%), and VPD (87.79%) had the lowest efficiency levels.

To minimize exergy destruction, the temperature differences (ΔT_H and ΔT_C) need to be approximately equal in value [20]. It is important to note that pinch analysis does not consider exergy destruction review. The typical design of a heat exchanger network is shown in Figure I. According to the schematic diagram, hot and cold streams were only separated by pinch points. Therefore, the heat exchanger network exclusively obeys the 3 pinch rules [21]. By applying principles aimed at minimizing exergy destruction, the temperature interval lines dividing hot and cold streams in the grid diagram need to be increased.

Table 2. Details of base case design utility requirements

Variable	Value
Hot external utilities	
Low-Pressure Steam	90.26 MW 147.5 TPH SOC: 40.5%
Cold external utilities	
Cooling water	52.76 MW 4650 TPH

The base case design of the heat exchanger comprises a total of 15 units divided into 3 stations. The first (purification process), second (evaporation process), and third stations (crystallization process) consist of 5 JHs, 5 evaporators, and 3 vacuum pans, respectively. As shown in Figure 1, the source of hot and cold external utilities in base case design was derived from Low-Pressure Steam operating at conditions of 2 Kg/cm^2.a at saturated condition and cooling water operating at 30ºC respectively. Details of base case design utility requirements have been summarized in Table 2.

In Figure 2, the simulation of the optimized heat exchanger network for the boiling house sulphitation process is presented. The results showed that there are several modification processes in the base case and optimized heat exchanger network. Tables 3 and 4 show hot and cold stream data for the optimized heat exchanger network of the boiling house sulphitation process in a sugar plant. The number of these streams was increased due to suggestions of some practical ways to improve exergetic efficiency and SOC.

The temperature difference and heat exchange load in heat transfer contribute primarily to exergy destruction. As shown in Table 1, the lowest exergetic efficiency belongs to JH1-1 (86.83%), VPA (87.05%), VPC (86.80%), and VPD (87.79%). Some practical recommendations exist for enhancing exergetic efficiency of the sulphitation process in a boiling house. These included the reduction of the temperature difference between the hot and cold streams and considering alterations in the type and configuration of the boiling house system.

Raw juice was heated up to 75°C using 3 juice heaters, namely JH1-1, JH1-2, and JH1-3. The primary heater was heated using vapor bleed 5th evaporator, vapor bleed 4th evaporator, and vapor bleed 5th evaporator, respectively. Subsequently, VPA, VPC, and VPD were heated by vapor bleed 2nd evaporator. In the optimized heat exchanger network, flash condensate from the preceding effect was used to heat the *n-th* effect evaporator.

Table 3. Hot stream data of optimized boiling house sulphitation process in sugar plant

No Stream	Stream	$\dot{m}$ (10^3 kg/hr)	T_{in} (°C)	T_{out} (°C)	Enthalpy (10^6 kJ/hr)
1	Raw juice	436.59	30.00	75.00	74.64
2	Sulph juice	436.59	75.00	105.00	52.58
3	Clear Juice	372.72	90.06	105.00	22.68
4	EV1 Juice	372.72	105.00	113.68	266.94
5	EV2 Juice	258.62	105.33	105.74	204.43
6	EV3 Juice	163.86	95.39	95.68	60.15
7	EV4 Juice	134.82	81.43	81.86	50.53
8	EV5 Juice	110.31	53.90	54.72	46.91
9	VPA syrup	93.92	54.94	67.13	66.52
10	VPC syrup	26.17	53.98	73.40	29.00
11	VPD syrup	44.72	55.31	86.65	35.72
12	Cond. EV1	121.17	120.27	120.27	7.44
13	Cond. ret	121.17	120.27	120.28	259.49

Table 4. Cold stream data of optimized boiling house sulphitation process in sugar plant

No stream	Stream	$\dot{m}$ (10^3 kg/hr)	T_{in} (°C)	T_{out} (°C)	Enthalpy (10^6 kJ/hr)
1	EV1 vap	114.10	113.68	113.16	253.75
2	EV2 vap	94.75	105.68	104.83	212.95
3	EV3 vap	29.04	95.46	94.52	66.08
4	EV4 vap	24.51	81.36	80.33	56.68
5	EV5 vap	23.35	54.72	52.55	55.61
6	VPA vap	27.77	67.13	52.55	66.68
7	VPC vap	12.09	73.40	52.56	29.11
8	VPD vap	14.51	86.65	52.58	34.99
9	BFW	120.79	138.93	126.27	7.45
10	FCEV1	1.96	104.83	104.83	4.41
11	FCEV2	4.31	94.52	94.52	9.82
12	FCEV3	6.53	80.33	80.33	15.08

The condensate from the first effect is taken directly back to the boilers. This is because it comprised the highest-quality condensate available for boiler feed, originating from the condensed exhaust steam/low-pressure steam. The transformer (TR-1) facilitated the use of exhaust steam/low-pressure steam (3.5 kg/cm2.a at the saturated condition) as the heating medium for condensation from evaporator 1. Condensate from Vacuum Pans and Juice Heaters was added to the combined stream to augment the process.

Rein et.al [22] reported several advantages of applying a condensate flash arrangement. Firstly, it led to the improvement of SOC due to the addition of vapor to the evaporator. Secondly, the loss incurred when condensate was simply taken to the storage, was eliminated. Thirdly, the condensate that was not directed to the boiler was subjected to a flash-down process to match the pressure within the final effect evaporator. With a temperature of approximately 80°C, this condensate is ideally suited for use in either the imbibition process or within the process area.

The composite curve of the boiling house sulphitation process is shown in Figure 4. Table 5 presents the data of heat exchange and exergetic efficiency for an optimized network, using a minimum temperature approach ΔT_{min} = 6°C. The composite curve provides the overall sources and sink temperature profile of the process. Several other benefits include the integration of process, HEN, and boiling house process simultaneously [23].

The optimization result shows a significant decrease in the consumption of hot external utilities, by 18.18% from the initial heating of 90.26 MW to 72.08 MW. Similarly, the consumption of cold external utilities decreased by 14.7% from the initial cooling of 52.76 MW to 44.99 MW. Heat optimization results have succeeded in obtaining a Maximum Energy Recovery (MER) of 254.88 MW.

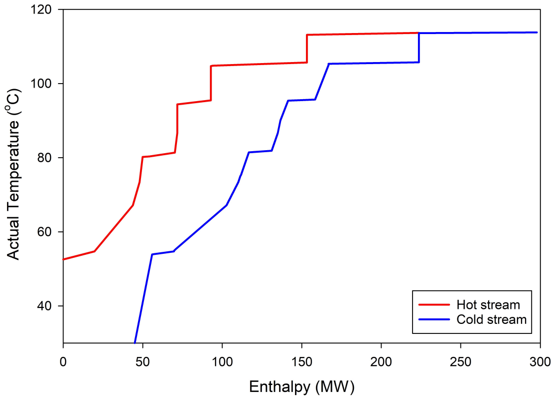

Figure 4. Actual composite curve

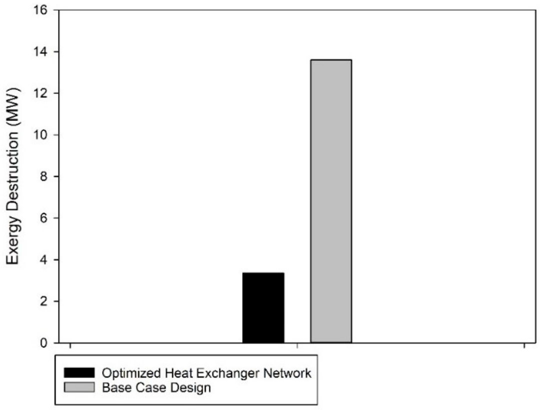

Figure 5. Comparison exergy destruction

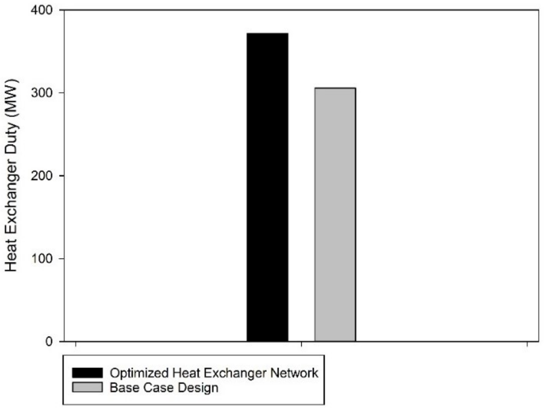

Figure 6. Comparison heat exchanger duty

Exergy analysis between base case design and optimization heat exchanger network has been presented in Tables 1 and 5. As shown in Figures 5 and 6, the optimization of energy within the heat exchanger network led to a successive decrease in exergy destruction by 10.25 MW. However, there was a corresponding increase in heat exchanger duty by 66.19 MW. This analysis suggests that post-optimization, there is a greater capacity for heat supply transfer to the cold flow. As heat duty rises, the W_{lost} of HEN drops. This shows that, while the amount of heat supplied increases, the heat lost during heat transfer process in HE decreases. As a result, HEN energy developed in this study is capable of producing more efficient heat transfer between hot and cold streams.

4. Conclusion

In conclusion, the study presented the methodology and results of applying both exergy and pinch analysis on an industrial scale, with the main focus on the boiling house sulphitation process. A total of 3 practical ways, incorporating pinch and exergy analysis methods, were used to improve the overall exergetic efficiency of the sulphitation process. First, Raw juice was heated up to 75°C using 3 juice heaters (JH's), adopting vapor bleed 5th evaporator, vapor bleed 4th evaporator, and vapor bleed 5th evaporator, as heating media, respectively. Second, VPA, VPC, and VPD were heated using a vapor bleed 2nd evaporator. Third, in an optimized heat exchanger network, flash condensate from the preceding effect was used to heat the *n-th* effect evaporator.

From the optimization result, the amount of hot external utilities was successfully reduced by 18.18% from the initial heating of 90.26 MW to 72.08 MW. Additionally, the amount of cold external utilities was successfully reduced by 14.7% from the initial cooling of 52.76 MW to 44.99 MW. Following energy optimization conducted on the heat exchanger network, the value of exergy destruction was reduced by 10.25 MW, while heat exchanger duty increased by 66.19 MW.

Nomenclature

E	Exergy flow (KJ/hr)
H	Specific enthalpy (KJ/Kg)
Q	Heat transfer (KJ/hr)
S	Entropy (KJ/Kg.K)
T	Temperature (oC)
η	Exergetic efficiency (%)
$\dot{m}$	Flowrate (Kg/hr)
$\dot{E}x$	Exergy rate (KJ/hr)

Subscripts

In	inlet state
Out	outlet state
O	dead state

Abbreviation used for blocks in flow diagrams

VP	Vacuum Pan
JH	Juice Heater
EV	Evaporator
C	Condenser

Table 5. Exergetic efficiency of optimized boiling house sulphitation process components

HE	Stream		T (ºC)		Q (kJ/hr)	m (kg/hr)	H (kJ/kg)		S (kJ/kg.K)		E (kJ/hr)	η
			In	Out			In	Out	In	Out		
JH1-1	Shell (h)	Bleed EV5	54.72	52.55	24418154.64	23351.12	3192.09	3441.85	0.33	1.10	248650.95	98.98
	Tube (c)	Raw Juice	30.00	45.00		436599.80	3377.00	3363.64	1.96	1.92		
JH1-2	Shell (h)	Bleed EV4	81.86	80.33	24856914.69	10749.26	3180.07	3732.38	0.43	1.99	410376.59	98.35
	Tube (c)	Raw juice	45.00	60.00		436599.80	3363.64	3350.04	1.92	1.88		
JH1-3	Shell (h)	Bleed EV3	95.68	94.52	25368340.97	11149.51	3173.95	3717.39	0.47	1.95	356507.64	98.59
	Tube (c)	Raw juice	60.00	75.00		436599.80	3350.04	3336.17	1.88	1.84		
JH2-1	Shell (h)	Bleed EV2	105.74	104.83	25957501.45	11550.14	3169.49	3706.27	0.50	1.92	251359.21	99.03
	Tube (c)	Sulphited juice	75.00	90.00		436599.80	3336.17	3321.97	1.84	1.80		
JH2-2	Shell (h)	Bleed EV1	113.68	113.16	26630755.82	11974.94	3166.05	3697.21	0.52	1.90	123243.67	99.54
	Tube (c)	Sulphited juice	90.00	105.00		436599.80	3321.97	3307.40	1.80	1.76		
JH3	Shell (h)	Bleed EV1	113.68	113.16	22689303.05	10202.60	3166.05	3697.21	0.52	1.90	104474.74	99.54
	Tube (c)	Clear Juice	90.06	105.00		372727.13	3332.95	3318.41	1.80	1.76		
EV1	Shell (h)	LPS	120.27	120.27	266948220.00	121172.54	3163.26	3689.44	0.54	1.88	810265.50	99.70
	Tube (c)	EV1 juice	105.00	113.68		372727.13	3318.41	3147.34	1.76	1.32		
EV2	Shell (h)	Bleed EV1	113.68	113.16	204429074.18	91924.77	3166.05	3697.21	0.52	1.90	762160.45	99.63
	Tube (c)	EV2 juice	105.33	105.74		258624.82	3139.09	2950.30	1.67	1.18		
EV3	Shell (h)	Bleed EV2	105.68	104.83	60148439.45	26765.19	3169.55	3706.30	0.50	1.92	285819.47	99.52
	Tube (c)	EV3 juice	95.39	95.68		163868.42	2823.55	2735.88	1.56	1.33		
EV4	Shell (h)	Bleed EV3	95.46	94.52	50530965.94	22212.30	3174.14	3717.49	0.47	1.95	355746.07	99.30
	Tube (c)	EV4 Juice	81.43	81.86		134824.06	2641.51	2551.99	1.51	1.26		
EV5	Shell (h)	Bleed EV4	81.36	80.33	46910345.68	20293.35	3180.46	3732.58	0.43	1.99	753108.77	98.39
	Tube (c)	EV5 Juice	53.90	54.72		110312.32	2412.43	2310.86	1.44	1.13		
VPA	Shell (h)	Bleed EV2	105.74	104.83	66524618.64	29601.02	3169.49	3706.27	0.50	1.92	1787410.44	97.31
	Tube (c)	VPA syrup	54.94	67.13		93926.74	2025.19	1856.02	1.32	0.81		
VPC	Shell (h)	Bleed EV2	105.74	104.83	29005489.71	12906.38	3169.49	3706.27	0.50	1.92	797054.24	97.25
	Tube (c)	VPC syrup	53.98	73.40		26178.88	2336.35	2071.72	1.42	0.62		
VPD	Shell (h)	Bleed EV2	105.74	104.83	35723692.41	15895.74	3169.49	3706.27	0.50	1.92	898133.78	97.49
	Tube (c)	VPD syrup	55.31	86.65		44727.30	1849.30	1658.53	1.18	0.61		
C-EV	Shell (h)	Bleed EV5	52.55	52.55	31190078.83	23351.12	3441.85	3760.88	1.10	2.07	365270.71	98.83
	Tube (c)	Cooling water	30.00	39.62		779695.35	3784.20	3774.64	2.15	2.12		
C-VA	Shell (h)	Bleed VPA	67.13	52.55	66686606.96	27774.85	3180.92	3754.38	0.31	2.07	781789.74	98.83
	Tube (c)	Cooling water	30.00	39.79		1638735.42	3784.20	3774.48	2.15	2.12		
C-VC	Shell (h)	Bleed VPC	73.40	52.56	29105512.34	12092.91	3169.09	3743.95	0.30	2.07	343640.92	98.82
	Tube (c)	Cooling water	30.00	39.79		715171.59	3784.20	3774.48	2.15	2.12		
C-VD	Shell (h)	Bleed VPD	86.65	52.58	34989103.74	14514.25	3131.20	3706.98	0.28	2.04	422759.64	98.79
	Tube (c)	Cooling water	30.00	39.79		859622.58	3784.20	3774.48	2.15	2.12		
TR-01	Shell (h)	Cond EV1	120.27	120.28	259499995.75	121172.54	3674.76	3163.25	1.84	0.54	2127154.81	99.18
	Tube (c)	Exhaust Steam	138.93	138.93		120796.19	3154.78	3667.88	0.58	1.83		
CEX	Shell (h)	Boiler Feed	138.93	126.27	7449531.04	120796.19	3667.88	3682.61	1.83	1.86	88414.04	98.81
	Tube (c)	Cond EV1	120.27	120.27		121172.54	3689.44	3674.76	1.88	1.84		

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