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Pinch Analysis of a Commercial-Scale Sugarcane Wax Accelerated-Solvent Extraction and Purification Process

[1]Wanwisa Skolpap, [2]Nuttawee Owat
Department of Chemical Engineering, School of Engineering, Thammasat University, Thailand
Email: swanwisa@engr.tu.ac.th
Department of Chemical Engineering, School of Engineering, Thammasat University, Thailand
Email: nuttaweeowat@gmail.com
Corresponding Author: Wanwisa Skolpap

--ABSTRACT--

The purpose of this research was to develop sugarcane wax extraction from pressmud of clarification process in sugar manufacturing plant using accelerated solvent extractions (ASE) and to optimize its heat recovery using pinch analysis. The sugarcane wax yield of 14.1% achieved from a developed commercial–scale ASE and purification process was comparable to the previously reported yield. At the minimum temperature difference of 12°C, selection of the most economical heat recovery of the heat exchanger network (HEN) alternative among eight alternatives designed by Aspen Energy Analyzer™ was based on an incremental net present value (ΔNPV). The most cost-effective HEN alternative could lower the total annual cost by 4% comparing to the current HEN.

Keywords: *Accelerated solvent extraction, Heat exchanger network, Pinch analysis, Process simulation, Sugarcane wax extraction*

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I. INTRODUCTION

Pressmud or filter cake consisting of sugar, fiber, wax, albuminoids, inorganic salts and dirt particles is a by-product residue of the clarification process in sugar factories [1]. The accumulation of these wastes cause environmental problems, thus pressmud disposal method is required. The recovery method of valuable substance from pressmud such as sugarcane wax not only adds values to the waste, but also decreases amount of disposed wastes. Sugarcane wax comprising alkanes, hydrocarbons, fatty acids, ketones, aldehydes, alcohols, esters, and steroids [2] is widely used in many applications, such as cosmetics, textiles, fruit and vegetable coating, leather, lubricants, adhesives, polishes, and pharmaceutical products [3]. Extraction is used for separation and recovery of chemical constituents from botanicals. Since Soxhlet extraction, a conventional extraction technique, has drawbacks of larger volume of solvent and longer extraction time required with lower extraction yield, alternative improved techniques such as microwave–assited extraction (MAE), ultrasonic–assisted extraction (UAE), supercritical fluid extraction (SFE) and accelerated solvent extraction (ASE) offer faster and more environmental friendly with higher yield.

MAE was first reported by [4]. Two common types of microwave-assisted exaction configuration are a closed extraction under controlled pressure and temperature and an open extractor under atmospheric pressure condition and controlled temperature at solvent boiling point. MAE enhances extraction efficiency by inducing high thermal energy via electromagnetic radiation in the range of 300 MHz to 300 GHz for heating the sample [5]. The solubility of various compounds to be extracted can be optimized by giving the solvents mixture ratio and controlling the temperature power. UAE uses ultrasonic energy above 20 kHz to produce cavitation bubbles; which in turn, collapse and generate higher shear resulting in complete extraction [6]. Moreover, UAE can be used in pretreatment technique for botanic material to enhance extraction performance. UAE is operated at lower extraction temperature and solvent volume yielding improvement of extraction and purity. Pulsed electric field (PEF) technology was successfully applied a pretreatment to increase extraction yield of juice from fruits [7]. The PEF extrusion of carotenoids from botanical materials was first patented that was based on the observation of positive effect of electroporation on the permeability of plant tissue [8]. Sub- and supercritical fluid extraction (SFE) are used as solvents with high feed to solvent ratio for extraction process of valuable product such as nutraceutical, pharmaceutical and food additives [9]. SFE commonly uses CO_2 as solvent since CO_2 is inexpensive, recyclable and non-hazardous substance. SFE allows operating at lower temperatures in the absence of oxygen and light. The elevation of solvent temperature and pressure is applied in extraction, known as accelerated solvent (ASE) or pressurized liquid extraction (PLE), by which can improve solvent solubility, diffusion rates for mass transfer into the solvent and lowers viscosity to increase solvent penetrability into the sample matrix. Consequently, it requires less extraction time and solvent consumption than Soxhlet and sonication [10]. Additionally, it achieves fast and reproducible extraction of samples especially natural metabolites. Study sugarcane wax extraction using various techniques that ASE gave higher yield of extracted sugarcane wax than Soxhlet and SFE techniques by a factor of 0.48 and 1.4, respectively [11].

Pinch analysis is a technique which aims to reduce utility consumption of chemical processes [12]&[13]. Apples pinch technology to minimize energy consumption and to design heat exchanger network of ethylbenzene plant. The annual energy cost can be reduced by 0.61 million USD [14].

The purpose of this study was to scale up from the bench–scale sugarcane wax extraction reported by [11] to a commercial–scale plant of sugarcane wax extraction process, using green ASE technology. The developed sugarcane wax extraction and purification process was further analyzed energy consumption of the process heating systems for suggesting its energy savings.

II. MATERIALS AND METHOD

2.1 Sugarcane wax extraction process.

A commercial–scale plant of sugarcane wax extraction process using accelerated ethanol as solvent (Fig. 1) which was developed based on the bench–scale extracting experiment of [11], was performed in Aspen Plus® simulator and thermodynamic model UNIQUAC. Before extraction, press mud was prepared by crushing and removing its moisture at 300°C. A daily feed rate of 800 kg pressmud and 960 kg ethanol were introduced to three parallel extractors which design temperature and pressure are 100°C and 100 bar [11]. After sugarcane wax is extracted, ethanol and wax were separated. Ethanol was removed by a vacuum evaporator (F101) for recovering and recycling operating at 0.05 atm and 70°C. To maintain levels of required ethanol in the process, ethanol was introduced by makeup feed 99.98 % of the ethanol into the evaporator. The sugarcane wax yield of 14.1% or kg/day which was obtained from the developed commercial–scale extraction and purification process, was comparable to yield of 13.32% reported by [11].

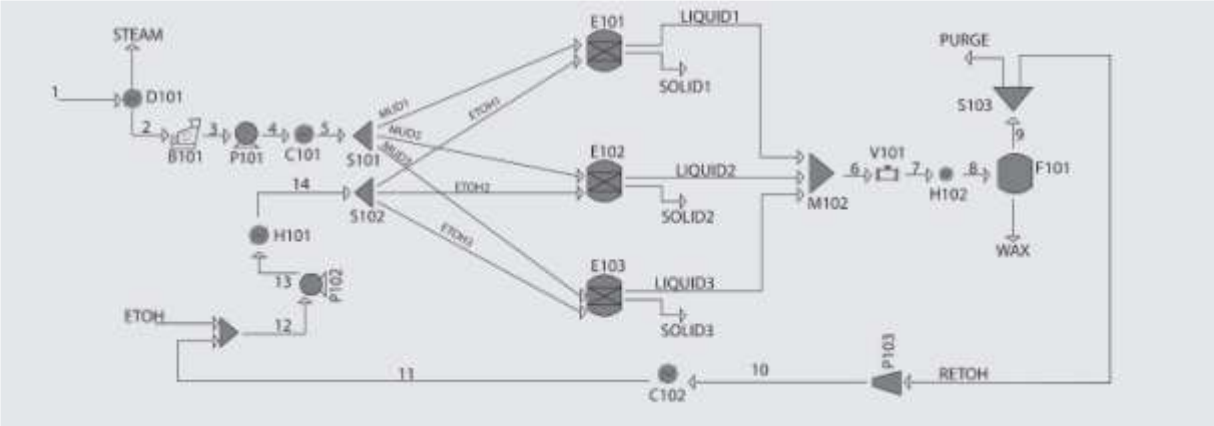

Fig. 1. A Developed Commercial-Scale Sugarcane Wax Extraction Plant Using Accelerated Solvent Extraction Method. The names of equipment are the followings: Crusher (B101), Dryer (D101), Cooler (C101 and C102), extractor (E101, E102 and E103) vacuum evaporator (F101), mixer (M101 and M102), heater (H101 and H102), compressor (P101 and P102), splitter (S101 and S102), valve (V101).

2.2 Pinch analysis

Pinch analysis which was first proposed by [14], applies the first and second laws of thermodynamic laws in evaluating feasible energy utilization to minimize external utilities requirement. A minimum temperature difference between hot and cold streams indicates a near optimal interchange between investment cost of integrating heat exchangers and cost of utilities. After thermal integration calculation using Aspen Plus® and Aspen Energy Analyzer™ based on a material and energy balance model, alternative designs of the heat exchangers network (HEN) were given by optimizing the heat recovery system and energy supply methods.

2.3 Economic Evaluation

Economic data, i.e., cost of heat exchanger (C_C), utilities and economic parameters, is illustrated in Table 1. The estimation of the percentage of energy savings and the net present value for selecting economical

HEN for the waste heat recovery system of the ASE process was based on the result of pinch analysis. Additionally, the economic estimation was based on 20-year project lifetime (n), 2-year construction and starts up period, annual interest rate (i) of 10 %, and annual working day of 320 days. All cost estimates were updated using the Marshall and Swift index which is 1593.7.

The assumptions for calculating investment are the followings assumptions, applied in the work by [15].
1. Investment for the required supplementary heat exchanger area is only considered.
2. Piping is taken into account “other costs.”
3. Heat exchanger averages are calculated from the base-case heat exchanger area, and the one-shell pass heat exchanger is assumed.
4. Energy prices are constant throughout the project life

Incremental net present values (ΔNPV) of the cash flows incorporated with capital investment and cost savings HENs is used as economic indicator to make feasible investment decisions among multiple alternatives.

Table1. Cost Data and Economic Parameters Used for the Economic Evaluation Utility

Economic data	Value	Description
Hot utility cost (USD/kWh)	6.84×10^{-3}	Lower steam pressure
Hot utility cost (USD/kWh)	1.53×10^{-3}	Fired heat
Cost of cold utility (USD/kWh)	9.85×10^{-3}	Refrigerant 1 at −25°C
Cold utility cost (USD/kWh)	3.6×10^{-6}	Air
Capital cost of a single stainless steel shell–and–tube heat exchanger (USD) [16]	$C_C = a + bA^c$ (1)	where Cost coefficients a, b, and c depending on construction materials are 30,800, 1,644, and 0.81.
Heat exchanger investment cost (USD)	$\text{Investment} = \Delta N \left(a + b \left(\frac{\Delta A}{\Delta N} \right)^c \right)$ (2) $\Delta N = \frac{\Delta A}{avg_{\text{shell}}}$ (3) $avg_{\text{shell}} = \frac{\Delta A}{N_{\text{shell}}}$ (4) $\Delta A = A_{\text{new, HEN}} - A_{\text{base, HEN}}$ (5)	where A is the area of the heat exchanger (m^2), $A_{\text{base, HEN}}$ is the total base-case heat exchanger network (HEN) of area (m^2), $A_{\text{new, HEN}}$ is the total alternative HEN area (m^2), avg_{shell} is the average size of the exchanger shell, and N_{shell} is the number of shells.
Uniform annual worth (USD/y)	$\text{AW} = \frac{(1+\frac{i}{100})^n}{n} \times \text{Investment}$ (6)	An equivalent series amount AW of the investment cost
Annual savings (USD/y)	$S = \left(\sum \text{HU}_{\text{base cost}} + \sum \text{CU}_{\text{base cost}} \right) - \left(\sum \text{HU}_{\text{new cost}} + \sum \text{CU}_{\text{new cost}} \right)$ (7)	where S is savings cost (USD). $\text{HU}_{\text{base cost}}$ and $\text{HU}_{\text{new cost}}$ are base-case and alternative-case hot utility costs (USD), respectively. $\text{CU}_{\text{base cost}}$ and $\text{CU}_{\text{new cost}}$ are base-case and alternative-case cold utility costs (USD), respectively.

Economic data	Value	Description
Saving percentage (%)	$\%S = \frac{\left(\sum \mathrm{HU}_{\text{base cost}} + \sum \mathrm{CU}_{\text{base cost}}\right)}{\left(\sum \mathrm{HU}_{\text{base cost}} + \sum \mathrm{CU}_{\text{base cost}}\right)} \frac{-\left(\sum \mathrm{HU}_{\text{new cost}} + \sum \mathrm{CU}_{\text{new cost}}\right)}{\left(\sum \mathrm{HU}_{\text{base cost}} + \sum \mathrm{CU}_{\text{base cost}}\right)}$ (8)	
ΔNPV (USD) [17]	$\Delta\mathrm{NPV} = S \cdot \frac{1+(1+i)^{-n}}{i} - \mathrm{Investment}$ (9)	Incremental net present values for each HEN

III. RESULT AND DISCUSSION

3.1 Determination of minimum temperature difference

Aspen Energy analyzer™ gives a range target plot of minimum total cost of the HEN as a function of the minimum approach temperature as shown in Fig. 2 At a variation of the minimum approach temperature, the total HEN costs are estimated using the best trade-offs amongst utility requirements, heat exchanger areas, and unit shell numbers. A pinch is identified by the minimum region between hot and cold streams. The overlap between hot and cold utility curves representing the amount of heat can be recovered while the non-overlap area represents amount of heat required from external utility. The maximum energy recovery leads to the minimum external utility requirement resulting in optimal energy savings. The smaller $\Delta T_{\min}$, the greater amount of heat can be recovered in the HEN causing a larger area of heat exchanger required. On the other hand, larger $\Delta T_{\min}$ indicates the decrease in heat recovery with the increase of utility required. As increasing $\Delta T_{\min}$ ranging from 12°C to 40°C, the total cost was changed insignificantly as shown in Fig. 2. Moreover, selecting $\Delta T_{\min}$ should take economic evaluation and experience into account [18]. Based on practical industrial–scale chemical processes, experience, the typical values of $\Delta T_{\min}$ are in the range of 10 and 20°C [19]. Thus, the $\Delta T_{\min}$ value of 12°C was used for calculating heat integration and exchanges between hot and cold utilities of the developed sugarcane wax extraction and purification process.

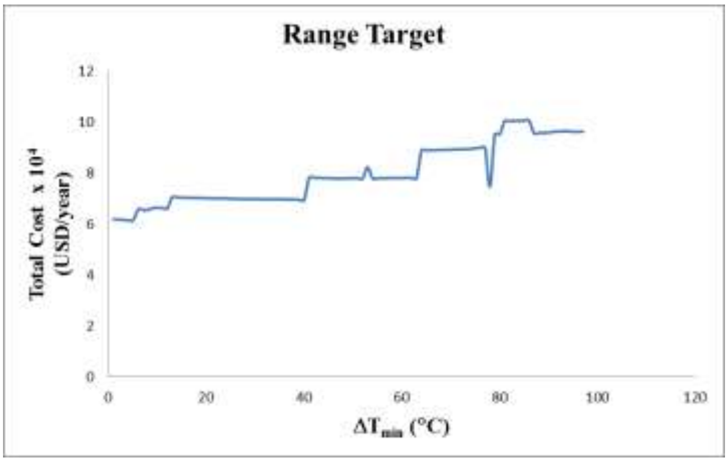

Fig.2. Plot of Range Targets

Prior to HEN design, a composite curve of temperature-enthalpy of hot and cold steams illustrated in Fig. 3. It gives information about maximum and minimum utility requirement of hot and cold streams. The pinch point is the closest temperature difference between the hot and cold utility curves ($\Delta T_{\min}$).

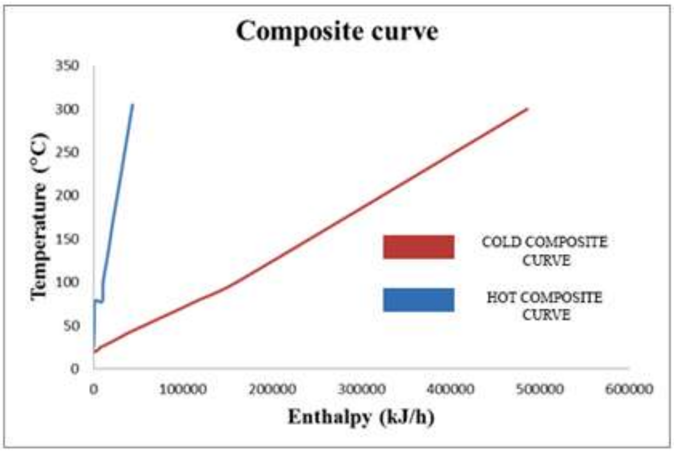

Fig.3. Composite Curve for the Sugarcane Wax Extraction and Purification Processes

The pinch temperature and the minimum requirement of heating and cooling utilities are characterized by the pinch technique. A grand composite curve shown in Fig. 4 was generated to provide the excess internal heat available within each temperature interval for selecting utilities by minimizing the use of expensive utilities.

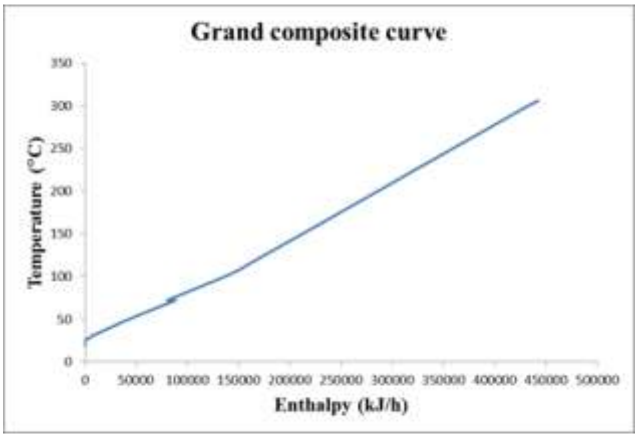

Fig.4. Grand Composite Curve for the Sugarcane Wax Extraction and Purification Processes

3.2 Heat Integration

Three hot and two cold streams of the current developed ASE and purification of sugarcane wax were identified by pinch technique as shown in Table 2. Then, the optimal thermal recovery was performed using Aspen Energy analyzer™ by which provided the HEN design information of the current ASE plant and alternative designs, i.e., options A, B, C, D, E, F, G, and H, about the surface heat transfer area required and the annual cost estimates for the specified heat duty as shown in Table 3.

Table2. Stream Data

Steam Name	Steam	Condition	T_{in} °C	T_{out} °C	Enthalpy kW
4_To_5	C1	Cold	19.78	70	13,348.59
13_To_14	H2	Cold	304.87	100	29,612.64
7_To_8	H3	Hot	232.85	25	14,073.88
10_To_11	C2	Hot	40.61	100	24,213.60
D101_heat	H1	Hot	25.00	300	448,200.21

Table3. Heat Exchanger Network Designs Using Pinch Analysis

Design	N_{shell}	$N_{\text{heat exchanger}}$	$\sum A_i$ (m^2)	Annual cost (USD/y)	Investment (USD)
Current design	12	9	8.77	13,191.88	252,867.40
Design A	12	10	8.69	13,229.13	252,679.11
Design B	11	9	8.44	13,771.56	251,645.19
Design C	8	6	9.97	13,966.15	220,547.22
Design D	8	7	4.59	15,956.77	235,296.31
Design E	13	8	5.49	16,001.16	343,025.01
Design F	12	7	5.36	16,543.59	342,782.84
Design G	6	6	4.29	16,818.28	224,438.55
Option H	5	5	4.80	17,646.10	215,402.92

Current design HEN and HEN alternatives are shown in Fig. 5a-5i. HEN alternatives were designed to achieve individual energy targets using pinch technology with the $\Delta T_{\min}$ of 12°C. External hot utilities are fire heater and LP steam, while external cold utilities are Air and Refrigerant1. The external utilities represented by thin lines in Fig. 5a-5i are as follows: (i) the white matches performed the internal heat recovery between two heat exchangers; the blue matches performed heat exchanging between external cold utility and hot steam and the red matches performed heat exchanging between external hot utility and cold steam. The demands of external energy of current design were 135 kW of hot utility and 12.14 kW of cold utility, while those of other HEN alternatives were 122.86 kW of hot utility and 0.056 kW of cold utility.

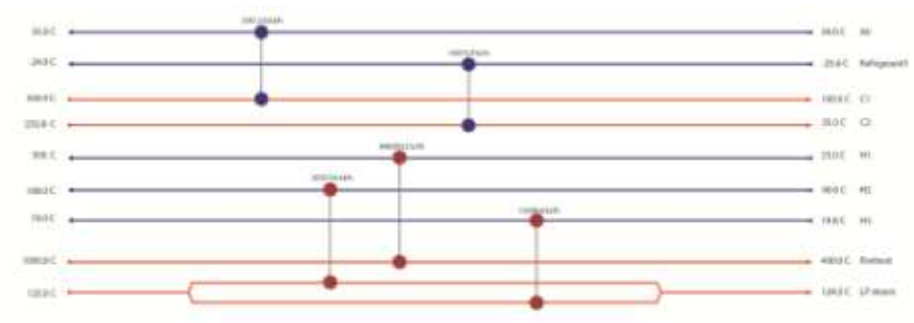

Fig.5a. HEN Configuration of the Current Design

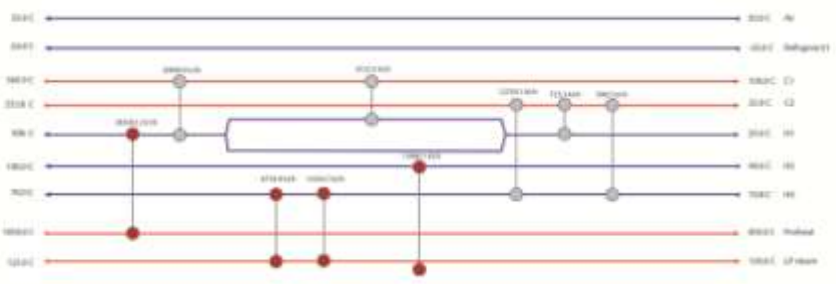

Fig.5b. HEN Configuration of the Design A

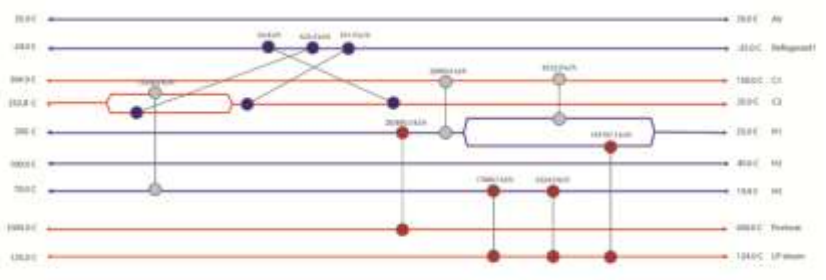

Fig.5c. HEN Configuration of the Design B

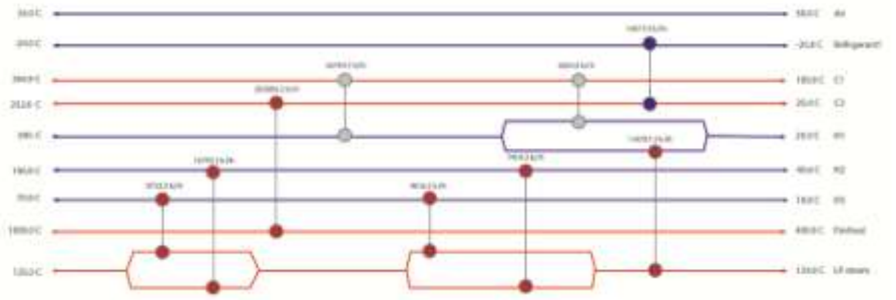

Figure 5d. HEN Configuration of the Design C

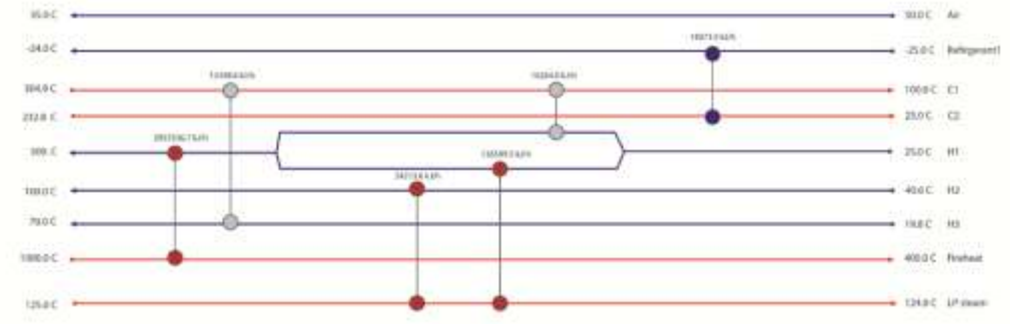

Fig.5e. HEN Configuration of the Design D

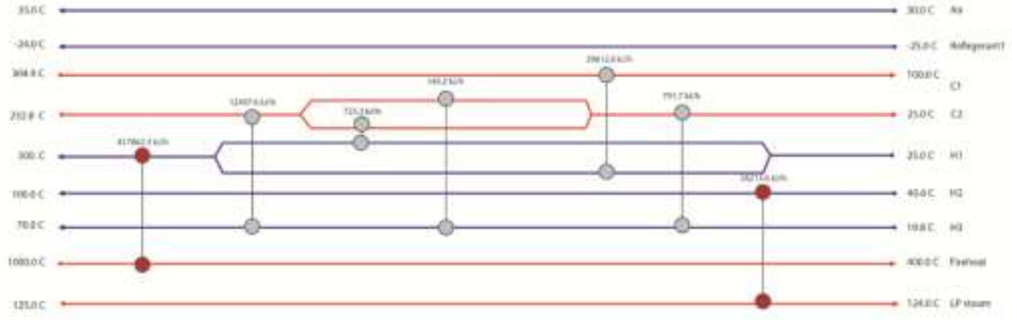

Fig.5f. HEN Configuration of the Design E

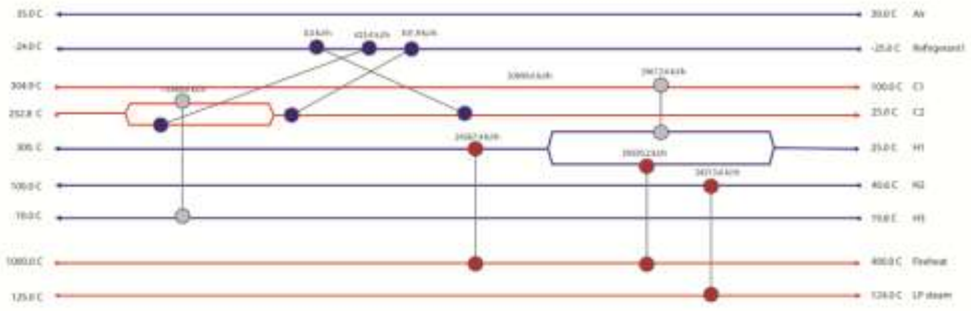

Fig.5g. HEN Configuration of the Design F

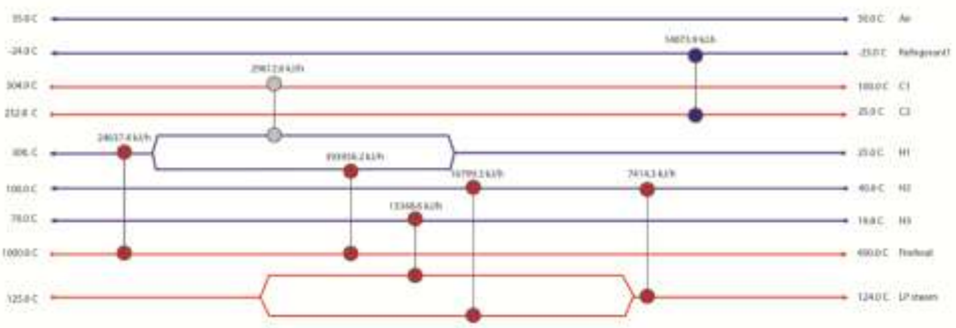

Fig.5h. HEN Configuration of the design G

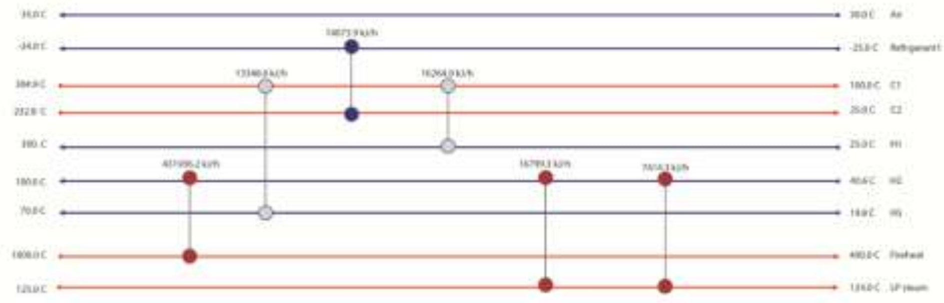

Fig.5i. HEN Configuration of the Design H

3.3 Economic analysis

Amongst eight HEN alternatives, option H showed the smallest heat transfer area required and the lowest annual cost as illustrated in Table 3. Results of estimated savings and ΔNPV shown in Table 4 are economic criteria in selecting suitable HEN alternative. A positive cost savings percentage suggests that the cost of base case H is less expensive comparing to that of alternatives, while a negative cost saving percentage suggests that the base case costs are greater than alternative designs. The utility cost of design H was 21.56%, 21.34% 18.12%, 16.96%, 5.12%, and 4.86% higher than that of alternatives A, B, C, D, E, and F, respectively. However, utility cost for design H was 4.92% less than the current design, while both design H and G had the same amount of utility cost. When comparing design H with other HEN alternatives, the highest positive ΔNPV is preferred to select optimal heat recovery in the process. This suggests that the HEN alternative H has more economic feasibility of investment.

Table4. NPV Comparison of design H

Comparison of options:	Savings (%)	ΔNPV (2017) (USD)
Design H versus current design	4.92	7,047.67
Design H versus Design A	-21.56	403,371.52
Design H versus Design B	-21.34	395,870.12
Design H versus Design C	-18.12	343,049.72
Design H versus Design D	-16.96	345,643.86
Design H versus Design E	-5.12	12,086.25
Design H versus Design F	-4.86	118,577.69
Design H versus Design G	0	101,706.54

Based on the economic evaluation, investment of design H was the most economically feasible. As shown in Fig. 5i, a fraction of the available flow rate of C1 stream was used to heat the H1 and H3 streams. However, the amount of heat transfer between C1 and H1 was insufficient, H1 obtained additional heat from fired heat as external utility. Similar to H2 steam, it obtained heat transferred from externally LP steam. C2 stream was cooled down by refrigerant1 as external utility. Compared to the current HEN, the most economical HEN alternative H could reduce annual utility cost and the total cost by 4.92% and 14.8%, respectively. The modified process flow sheet of sugarcane wax extraction and purification plant based on the HEN design H is shown in Fig. 6.

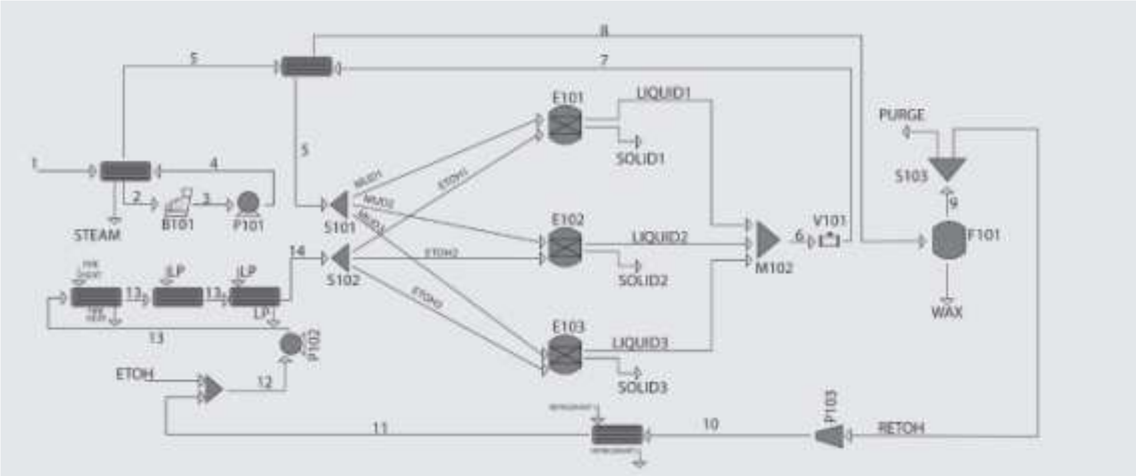

Fig.6. Modified process flow sheet of sugarcane wax extraction and purification plant based on the HEN design H

IV. CONCLUSION

Heat integration analysis of the pinch technique using Aspen plus® and Aspen Energy Analyzer™ was successfully applied for designing and satisfying energy target of a developed commercial-scale sugarcane wax extraction and purification plant by accelerated ethanol extraction technique. The HEN alternative H was more economically feasible investment with minimum heat transfer area required and annual cost.

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