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Circular integration of crude distillation process

Chanikan Bubpha, Kitipat Siemanond*

The Petroleum and Petrochemical College, Chulalongkorn University, Bangkok, Thailand
kitipat.s@chula.ac.th

Circular integration (CI) of crude distillation unit (CDU) is introduced the closed loop to recover waste heat from hot product streams to heat the cold crude steams and reduce the external energy resulting in lower CO_2 emission and utilities cost saving. The stagewise superstructure by Yee and Grossmann (1990) is applied to retrofit heat exchanger network (HEN) of crude preheat train supported by variable heat capacity as a function of temperature. The objective function for HENS is to maximize Net Present Value (NPV) of retrofitted HEN which relates to maximizing utilities cost saving. The optimization problem is solved by using General Algebraic Modelling System (GAMS) with DICOPT optimization solver. The HEN retrofit result shows that this model can reduce 65.44% of CO_2 emission and achieve 12,584,244.74 $ of NPV.

1. Introduction

CDU unit is the process in refinery and for separation of various crude fractions by their boiling points. The resource of this process is crude oil containing mixture of hydrocarbons with impurities of salts and water, which need to be removed by desalter before entering the distillation column to avoid corrosion of equipment in the crude preheat train (Dawe and Lucas, 2000). The furnace is required to heating up the desalted crude by heat of combustion. Therefore, this process requires external hot utilities for heating process causing large amount of direct CO_2 emissions. The refinery is the third largest direct Greenhouse Gas (GHG) emissions reported about 177.6 million metric tons CO_2e (EPA, 2019). The carbon emissions caused climate change and increasing of smog and air pollution (Osmanski, 2020) which cause humans respiratory disease. The energy efficiency improvement of crude preheat train reduces the energy consumption and CO_2 emission at the furnace by heat recovery. The heat recovery can be achieved by reusing waste heat from the process hot streams of petroleum products to preheat process cold stream of crude. Heat and Water Recovery System (HWRS) proposed by Yoo et al. can achieve 4.348% reduction in CO_2 emission and 20.29% reduction in fuel consumption by using hot flue gases as heat source to preheat water from water desalination (Yoo et al., 2019). Due to the increase of population, industrialization and standard of living, resulting in declining natural resources, global climate changes and risk to ecosystem, the sustainability plays the important role by balancing three principle including environmental protection, economic growth, and societal equity (El-Halwagi, 2017). These balancing also called circular integration which refers to Circular Economy (CE), Process Integration (PI), and Industrial Ecology (IE) (Walmsley et al., 2019). The Process Integration is developed to obtain the sustainable design focusing on the optimal design of HEN retrofit for reducing energy demand relating to the cost-efficiency, and the cost of new equipment and piping modifications (Smith, 2017). The retrofitting heat exchanger network can be achieved by relocation of heat exchanger, re-piping or adding new heat exchanger (Sieniutycz and Jezowski, 2018). Heat integration had been applied in crude distillation unit using HEN which the hot-product streams are used to heat up the cold-feed streams before entering distillation with decrease of utility consumption (Sieniutycz and Jezowski, 2018). The heat integration in pharmaceutical processing facility by transferring heat from hot to cold streams reduces hot utility from 4870 kW to 2620 kW and cold utility from 2300 kW to 50 kW (El-Halwagi, 2017).

2. Methodology

This study aims to optimize the problem of HEN retrofitting for crude preheat train. The CDU is simulated by PRO/II simulation software to collect the stream data, like specific heat capacity (Cp), flowrate (F) and Temperature (T) of hot and cold process streams. These data are parameters used for Mixed Integer Non-Linear Programming (MINLP) optimization to retrofit crude preheat train. Stage-wise superstructure (Yee and Grossmann, 1990) is applied to the HEN retrofit model with variable heat capacity which is the function of temperature (Sreepathi and Rangaiah, 2015) to find the general form of heat transfer rate (Q) under variable heat capacity shown in Eq 1. Assume $Cp(T) = eT^2 + fT + g$.

Then, $Q = \int_{T_2}^{T_1} F \cdot Cp(T)\, dT$

$$= F \cdot \int_{T_2}^{T_1} (eT^2 + fT + g)\, dT$$

$$= F \cdot \left(\frac{eT^3}{3} + \frac{fT^2}{2} + gT \Big|_{T_2}^{T_1} \right)$$

$$= F \cdot \left[\left(\frac{eT_1^3}{3} + \frac{fT_1^2}{2} + gT_1 + c \right) - \left(\frac{eT_2^3}{3} + \frac{fT_2^2}{2} + gT_2 + c \right) \right]$$

where $\frac{e}{3} = a$, $\frac{f}{2} = aa$ and $g = aaa$

$$Q = F . \left[\left(a \cdot T_1^3 + aa \cdot T_1^2 + aaa \cdot T_1 \right) - \left(a \cdot T_2^3 + aa \cdot T_2^2 + aaa \cdot T_2 \right) \right] \quad (1)$$

2.1 Objective function for HEN retrofit

This objective function is used to maximize the Net Present Value (NPV) as follows:

$$\text{Maximize NPV} = \sum_{y=1}^{n} \frac{\sum_i CCU(qcuold_i - qcu_i) + \sum_j CHU(qhuold_j - qhu_j)_y}{(1+i)^y}$$

$$- \sum_i \sum_j \sum_k CF_{ij} \times \max\left(0, \left(z_{ijk} - zold_{ijk}\right)\right) - \sum_i CF_{i,CU} \times \max(0, (zcu_i - zcuold_i))$$

$$- \sum_j CF_{j,HU} \times \max(0, (zhu_j - zhuold_j)) - \sum_i \sum_j \sum_k C_{ij} \max(0, (Area_{ijk} - Areaold_{ijk}))^{B_{ij}}$$

$$- \sum_i C_{i,CU} \max(0, (Area_i - AreaCold_i))^{B_{i,CU}} - \sum_j C_{j,HU} \max(0, (Area_j - AreaHold_j))^{B_{j,HU}}$$

Where n = lifetime in years, and I = annual interest rate

$zold_{ijk}$, $zcuold_i$, and $zhuold_j$ are binary variables for base-case process, cold-utility, and hot-utility exchangers, respectively.

$Areaold_{ijk}$, $AreaCold_i$, and $AreaHold_j$ are area for base-case process, cold-utility, and hot-utility exchangers, respectively.

2.2 Overall heat balances of each stream for variable heat capacity

An overall heat balances of hot (i) and cold (j) process streams are needed to calculated heating (qhu_j) and cooling (qcu_i) duties.

$$Fi \cdot \left[\left(a \cdot TINI^3 + aa \cdot TINI^2 + aaa \cdot TINI \right) - \left(a \cdot TOUTI^3 + aa \cdot TOUTI^2 + aaa \cdot TOUTI \right) \right] = \sum_{j \in CP} \sum_{k \in ST} qijk + qcui, \quad i \in HP$$

$$Fj \cdot \left[\left(d \cdot TOUTJ^3 + dd \cdot TOUTJ^2 + ddd \cdot TOUTJ \right) - \left(d \cdot TINJ^3 + dd \cdot TINJ^2 + ddd \cdot TINJ \right) \right] = \sum_{i \in HP} \sum_{k \in ST} qijk + qhuj, \quad j \in CP \quad (2)$$

2.3 Heat balances at each stage

An energy balances of hot (i) and cold (j) process streams are also needed to determine the temperature at each stage of the superstructure. The set of k = 1, …, NOK is used to represent the stage number while the set of k = 1, …, NOK+1 is used to define the temperature location of temperature stage.

$$Fi \cdot \left[\left(a \cdot ti_{i,k}^3 + aa \cdot ti_{i,k}^2 + aaa \cdot ti_{i,k} \right) - \left(a \cdot ti_{i,k+1}^3 + aa \cdot ti_{i,k+1}^2 + aaa \cdot ti_{i,k+1} \right) \right] = \sum_{j \in CP} \sum_{k \in ST} qijk \quad i \in HP, , k \in ST$$

$$Fj \cdot \left[\left(a \cdot tj_{j,k}^3 + aa \cdot tj_{j,k}^2 + aaa \cdot tj_{j,k} \right) - \left(a \cdot tj_{j,k+1}^3 + aa \cdot tj_{j,k+1}^2 + aaa \cdot tj_{j,k+1} \right) \right] = \sum_{i \in HP} \sum_{k \in ST} qijk \quad j \in CP, , k \in ST \quad (3)$$

2.4 Hot utility load (HU) and cold utility load (CU)

Hot (qhu_i) and cold (qcu_j) utility requirements are determined for each process stream. The temperature location of stage 1 or NOK+1 can be relaxed because cold and hot utility loading will replace the deficit or surplus energy of that stream, respectively.

$$Fi\left[\left(a\cdot ti_{i,nok+1}{}^{3}+aa\cdot ti_{i,nok+1}{}^{2}+aaa\cdot ti_{i,nok+1}\right)-\left(a\cdot TOUTI_i{}^{3}+aa\cdot TOUTI_i{}^{2}+aaa\cdot TOUTI_i\right)\right]=qcu_i,\quad i\in HP$$

$$Fj.\left[\left(a\cdot TOUTJj^{3}+aa\cdot TOUTJj^{2}+aaa\cdot TOUTJj\right)-\left(a\cdot tj_{j,1}{}^{3}+aa\cdot tj_{j,1}{}^{2}+aaa\cdot tj_{j,1}\right)\right]=qhu_j,\quad j\in CP \qquad (4)$$

2.5 Assignment of superstructure inlet temperatures

Fixed inlet temperature (TIN) is assigned as the inlet temperature to the superstructure.

$$TINI = Ti_{i,1}, \qquad i\in HP$$
$$TINJ = Tj_{j,nok+1}, \qquad j\in CP \qquad (5)$$

2.6 Feasibility of temperatures

defines the stream temperature on the left-hand side is higher than right-hand side location of each stage. Thus, temperature at stage location k is always higher than stage location k+1 for temperature stage k.

$$ti_{i,k} \geq ti_{i,k+1}, \qquad i\in HP,\ k\in ST$$
$$tj_{j,k} \geq tj_{j,k+1}, \qquad j\in CP,\ k\in ST$$
$$TOUTI_i \leq ti_{i,nok+1}, \qquad i\in HP$$
$$TOUTJ_j \geq tj_{j,1}, \qquad j\in CP \qquad (6)$$

2.7 Calculation of approach temperatures

These constraints are used to ensure that temperature of hot stream (i) is higher than cold stream (j), to specify temperature difference. The binary variables are used to activate when the match is occurred, zijk is 1, otherwise, zijk is 0. The temperature difference between hot and cold stream at any stage (dt_{ijk}) must be at least Exchanger minimum approach temperature (EMAT).

$$dt_{ijk} \leq ti_{i,k} - tj_{j,k} + gamma\cdot(1-z_{ijk}), \qquad i\in HP,\ j\in CP,\ k\in ST$$

$$dt_{ijk+1} \leq ti_{i,k+1} - tj_{j,k+1} + gamma\cdot(1-z_{ijk}) \qquad i\in HP,\ j\in CP,\ k\in ST$$

$$dtcu_i \leq ti_{i,nok+1} - tcuout + \sum_{j\in CP} gamma\cdot(1-zcu_i), \quad i\in HP$$

$$dthu_j \leq thuout - tj_{j,1} + \sum_{i\in HP} gamma\cdot(1-zhu_j), \qquad j\in CP$$

$$dtcu2_i \leq TOUTI_i - tcuin + \sum_{j\in CP} gamma\cdot(1-zcu_i) \quad i\in HP \qquad (7)$$

where

dt_{ijk}, dt_{ijk+1}, $dtcu_i$, $dtcu2_i$, $dthu_j$, $dthu2_j \geq EMAT$
gamma = max [0, TINJj–TINIi, TINJj –TOUTIi, TOUTJj–TINIi, TOUTJj –TOUTIi]

2.8 Logical constraints

These constraints are used to specify the existing of heat exchanger between hot stream (i) and cold stream (j) in stage (k) and the utilities at each stream by using binary variable which are zijk for the stream match, zcui for matches involving cold utility, and zhuj for matches involving hot utility. If process stream matching exists, binary variable will be 1.

$$qijk - \min(echi,eccj)\ zijk \leq 0, \qquad i\in HP,\ j\in CP,\ k\in ST$$
$$Qcui - ech\cdot zcui \leq 0, \qquad i\in HP$$
$$Qhuj - ecc\cdot zhuj \leq 0, \qquad j\in CP \qquad (8)$$

where z_{ijk}, zcu_i, zhu_j = 0,1

$$ech_i = F_j.Cp_i\,(TINI_i - TOUTJ_j)$$
$$ecc_j = F_j.Cp_j\,(TOUTJ_j - TINI_j)$$

2.9 The Log Mean Temperature Difference (LMTD)

Chen approximation for exchanger temperature approach calculation is used to avoid numerical difficulties when the approach temperatures on both Sides of exchanger matching are equal:

$$LMTDijk = \left[\left(dt_{ijk}\right)\left(dt_{ijk+1}\right)\frac{dt_{ijk}+dt_{ijk+1}}{2}\right]^{\frac{1}{3}}$$

$$LMTDCUi = \left[\left(dtcu_i\right)\left(dtcu2_i\right)\frac{dtcu_i+dtcu2_i}{2}\right]^{\frac{1}{3}}$$

$$LMTDHUj = \left[\left(dthu_j\right)\left(dthu2_j\right)\frac{dthu_j+dthu2_j}{2}\right]^{\frac{1}{3}} \qquad (9)$$

2.10 Area calculation

If heat duty matching (q_{ijk}) occurs, the area of process cold utility and hot utility is calculated.

$$Aqijk = \sum_{i\in HP}\sum_{j\in CP}\sum_{k\in ST}\left[\frac{q_{ijk}}{U_{ij}\cdot LMTD_{ijk}}\right], \qquad i\in HP,\ j\in CP,\ k\in ST$$

$$Acui = \sum_{i\in CP}\left[\frac{qcu_i}{U_{i,CU}\cdot LMTD_{i,CU}}\right], \qquad i\in HP$$

$$Ahui = \sum_{j\in HP}\left[\frac{qhu_j}{U_{j,HU}\cdot LMTD_{j,HU}}\right], \qquad j\in CP \qquad (10)$$

where

$$\frac{1}{U_{ij}}=\frac{1}{h_i}+\frac{1}{h_j},\quad \frac{1}{U_{i,CU}}=\frac{1}{h_i}+\frac{1}{h_{CU}},\quad \frac{1}{U_{i,CU}}=\frac{1}{h_i}+\frac{1}{h_{CU}}$$

3. Result and discussion

3.1 Crude distillation unit as base case

Base-case crude distillation unit was simulated by Pro/II (version10) simulation containing 4 hot product streams (H1, H2, H3, and H4) and 2 cold crude streams (C1 and C2) with 4 process exchangers (E1, E2, E3, and E4), 3 coolers (CU1, CU2, and CU3) and 2 heaters (HU1 and HU2) as shown in Figure 1 and 2. The stream and economic cost data of base-case of exchangers are shown in Table 1. From this base-case crude preheat train, the energy consumption of hot and cold utilities, and the area of heat exchanger and utilities are identified as base case are shown in Table 2.

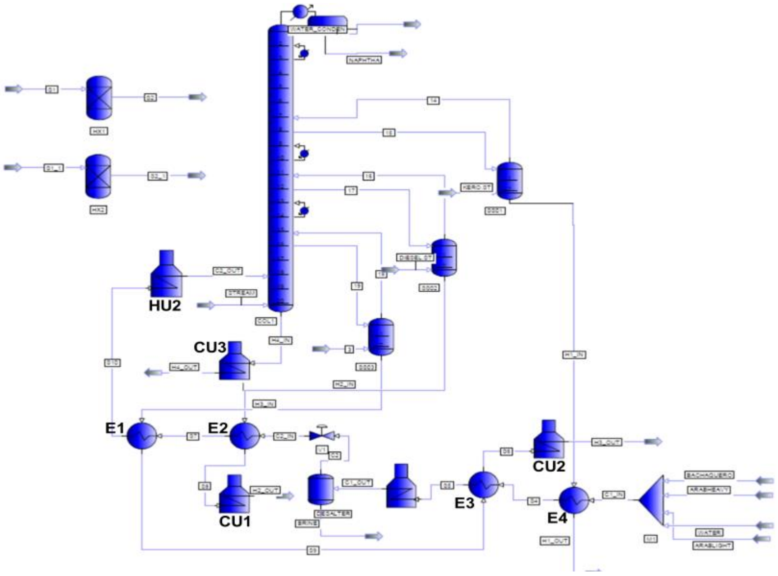

Figure 1: Existing process flow diagram for base-case crude preheat train by PRO/II

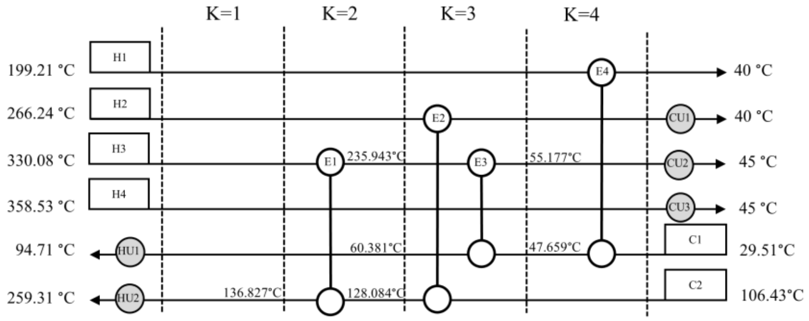

Figure 2 Existing grid diagram for base-case crude preheat train

Table 1: Process streams and economic cost data.

Stream	TIN	TOUT	Flowrate	Cp = aT^2+bT+c (kJ/kg·°C)			h	Cost
	(°C)	(°C)	(kg/s)	a	b	c	(kW/m^2·°C)	($/kW·year)
Hot streams								
H1	199.21	40	25.3275	-2.2990E-06	4.4100E-03	1.7680	0.2	
H2	266.05	40	27.0459	-2.0260E-06	4.4046E-03	1.6882	0.2	
H3	330.08	45	16.1855	-1.7748E-06	4.3359E-03	1.6511	0.2	
H4	358.52	45	105.789	-1.8025E-06	4.3126E-03	1.5840	0.2	
Cold streams								
C1	29.51	94.71	237.398	-1.6601E-05	5.2186E-03	1.9368	0.2	
C2	106.43	259.31	212.022	-3.5816E-06	4.4560E-03	1.7209	0.2	
Utilities								
CU	15	28	-	-	-	-	0.53	10
HU	400	400	-	-	-	-	0.53	100
New heat exchanger cost ($): 250,000 + 550 ΔA								
Additional area cost for existing heat exchangers ($): 550ΔA								
Project lifetime: 3 years								
Annual interest rate: 0%								

3.2 Optimization and Validation results

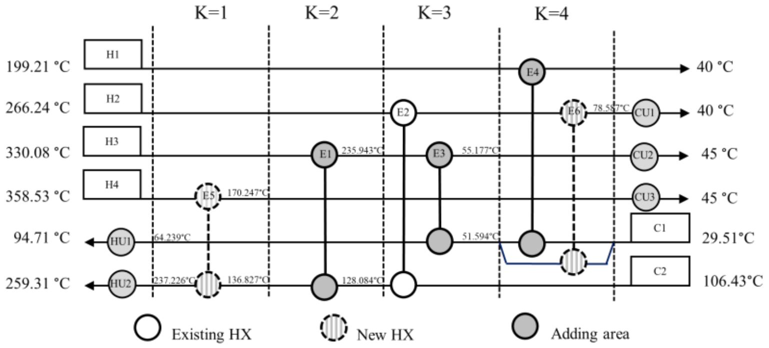

Figure 3: Optimal retrofitting HEN configuration by GAMS.

The stream and economic cost data were used to retrofit the base-case HEN with the maximum NPV through optimization in GAMS by using 4-stage superstructure model with variable Cp and exchanger minimum approach temperature (EMAT) of 3°C. The result of HEN retrofit model requires 2 new heat exchangers (E5 and E6) and additional area of three existing exchangers (E1, E3, and E4) as shown in Figure 3 and Table 2. The result shows the hot utility (HU) consumption reduces from 82,102.12 to 28,446.53 kW (65.35% saving in HU) and cold utility (CU) consumption reduces from 82,817.99 to 29,162.40 kW (67.79% saving in CU). NPV of this solution is $12,584,244.74 over 3 years with annual interest rate equal to 0 %. These results are validated by fixing hot - and-cold-stream temperature of HEN and HU. The error between optimization and validation result is shown in Table 3. The difference between these two results comes from the difference of LMTD approximation and the inlet and outlet temperature of heat exchanger and utilities. In table 4, the compared of total CO_2 emission and total energy consumption for the CDU without HEN, the base case and retrofitting HEN show this model recover more heat to reduce external utilities consumption the utilities cost and CO_2 emission by reducing the fuel consumption usage about 65.44% of CO_2 emission (4.7612 to 1.6457 kg/s) as shown in table 4.

Table 2: the energy consumption of hot and cold utilities, and the area of heat exchanger and utilities of base-case and retrofit HEN from GAMS.

Unit	Heat Duty (kW)		Area (m^2)	
	Base Case	Retrofit	Base Case	Retrofit
E1	4,167.297	4,167.297	284.368	284.638
E2	10,073.725	10,073.725	2,361.281	2,361.281
E3	6,553.770	6,553.770	1,325.718	1,734.801
E4	9,104.049	9,104.049	1,802.724	1,833.564
E5	-	5,1642.71	-	7,601.185
E6	-	2,012.878	-	362.44
HU1	18,255.899	1,6243.02	390.268	349.261
HU2	63,846.224	12,203.513	2,248.617	554.873
CU1	4,039.571	2,026.693	564.554	384.598
CU2	307.033	307.033	74.023	74.023
CU3	78,471.388	26,828.678	4,478.999	2,579.414

Table 3: The Optimization and validation result of retrofitting HEN.

Unit	**GAMS**		**PRO/II**		**% Error**	
	Q (kW)	Area (m^2)	Q (kW)	Area (m^2)	Q	A
E1	4,167.297	284.638	4,165.97	285.208	0.03	0.20
E2	10,073.725	2,361.281	10,076.25	2,246.911	0.03	5.09
E3	6,553.770	1,734.801	6,556.80	1,496.064	0.05	15.96
E4	9,104.049	1,833.564	9,026.00	1,739.231	0.86	5.42
E5	51,642.710	7,601.185	51,645.48	7,323.709	0.01	3.79
E6	2,012.878	362.440	2,011.20	362.149	0.08	0.08
HU1	16,243.020	349.261	16,496.99	3,55.2425	1.54	1.68
HU2	12,203.513	554.873	16,652.38	742.579	26.72	25.28
CU1	2,026.693	384.598	2,027.51	385.171	0.04	0.15
CU2	307.033	74.023	307.26	74.182	0.07	0.21
CU3	26,828.678	2,579.414	26,849.74	2,567.496	0.08	0.46

Table 4: The result comparison of base case and retrofitting HEN.

	Base case		Retrofit	
	GAMS	PRO/II	GAMS	PRO/II
CO2 emission (fuel consumption)				
HU1 (Kg/s)	-	1.2057	-	0.8190
HU2 (Kg/s)	-	3.5555	-	0.8267
Total energy consumption				
HU (KW)	82,102.12	95,903.38	28,446.53	33,149.37
CU (KW)	82,817.99	82,847.09	29,162.40	29,184.51
NPV ($) (3 years)	-	-	12,584,244.74	15,537,729.81

4.Conclusion

To make the model more realistic, variable heat capacity is used in stage-wise superstructure model to do HEN retrofit. Circular Integration (CI) is introduced to design the closed loop by using heat recovery that transfer heat between the hot product streams and cold crude feed streams which is also friendly to environment and health by reducing the CO_2 emission via less fuel consumption in combustion reaction. The retrofitting HEN is optimized by using GAMS software and then this retrofitting HEN is validated by PRO/II simulation software. The installed exchangers for retrofitting HEN on CDU can reduce CO_2 emission about 65.44% of CDU base case. This model can achieve NPV of $ 12,584,244.74. The model also has some validation error with PRO/II resulting from difference of LMTD approximation and the inlet and outlet temperature of heat exchanger and utilities.

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