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Retrofit of Refinery Heat Exchanger Network under Different Kinds of Crude Oil by Pinch Design Method using Mathematical Programming

Warumporn Pejpichestakul[a], Kitipat Siemanond[*a,b]

[a] The Petroleum and Petrochemical College, Chulalongkorn University, Chulalongkorn Soi 12, Phayathai Rd., Pathumwan, Bangkok 10330, Thailand
[b] National Center of Excellence for Petroleum, Petrochemicals and Advanced Materials, Chulalongkorn Soi 12, Phayathai Rd., Pathumwan, Bangkok 10330, Thailand
kitipat.s@chula.ac.th

Crude distillation units (CDUs) in refineries are major consumers of energy. Because of the high energy consumption of the crude furnace in the crude preheat train, heat integration by retrofitting the heat exchanger network (HEN) is presented in this research using a retrofit potential program and stage-model mathematical programming. The retrofit potential program from Kosol (2012) based on pinch technology was used to identify the optimum heat recovery approach temperature (HRAT). The n-stage model from Zamora and Grossman (1996), a mathematical programming using General Algebraic Modelling System (GAMS), was used to generate the retrofitted HEN with a minimum number of exchangers and maximum heat recovery at pinch exchangers match as an objective function. The simulation software (Pro/II) was used to validate designs and perform total utility consumption. An example of a CDU was simulated with light, medium and heavy crude oil feed for operating periods of 100, 150 and 100 days per year, respectively. The retrofit of the crude preheat train was applied to find the optimal and most profitable HEN design that yields the highest net present value (NPV).

1. Introduction

Energy conservation has become more important as public awareness and concerns regarding global warming and energy shortage continue to grow. Naturally, energy management has been applied to refineries as they are the most energy-intensive operations in the manufacturing industry. Crude distillation units (CDUs) are major energy-consuming units and therefore require extensive energy management. There are many ways to increase energy efficiency, and heat exchanger network (HEN) design and process heat integration are widely used methods. Heat transfer from hot products and pump-around streams to the crude feed by the applications of HEN reduces the energy demands of both coolers and furnaces. This reduction of energy demands diminishes the operating cost while increases the capital cost for exchanger area installation, therefore, the retrofit design is more preferable than the grass-roots design for oil refineries. In the real situation, the uncertain quality of crude oil in the market and changes in the quality of crude from traditional sources motivate the HEN retrofit to be operated under multiple periods for greater flexibility. The application of energy cost and capital cost trade-off from the retrofit technique of the pinch design method proposed by Tjoe and Linnhoff (1986), integrated with thermodynamics properties, provides the energy saving plots and optimum target. The n-stage model proposed by Zamora and Grossmann (1996) was applied to design the HENs and identify structural modifications. The stage model has also been applied to a real-case problem of a refinery in Thailand by Promvitak et al. (2009). Yimyam and Siemanond (2012) proposed the retrofit of a crude preheat train with multiple types of crude oil using a CDU with preflash drum problems, and the process proved to be energy-effective. In view of the current energy crisis and uncertainty in feedstock properties, a retrofit HEN design that is applicable to various raw materials means increased flexibility with maximum profit.

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2. Methodology

2.1 Targeting step by pinch design method

The pinch design method was applied to optimize existing HEN with thermodynamics properties considerations. The energy cost and capital cost trade-off from the retrofit technique is applied to yield the optimum heat recovery approach temperature (HRAT). This research used the retrofit potential program developed by Kosol (2012) using Visual Basic for Applications (VBA) to target the optimum ∆Tmin or HRAT and optimum pinch temperature automatically at the maximum net present value (NPV). The optimum HRAT from this step is used in a further procedure.

2.2 HEN retrofit step by n-stage model

The optimum HRAT from the targeting step is used as a constraint for HEN design by n-stage model with mixed integer linear programming (MILP) model using GAMS. The objective function is to minimize the number of exchangers with maximum heat recovery at pinch exchangers match with the algorithm shown in Figure 1. Pinch exchangers have exchanger minimum approach temperature (EMAT) equal to HRAT from the previous step while the rest of the exchangers have EMAT equal to 5°C.

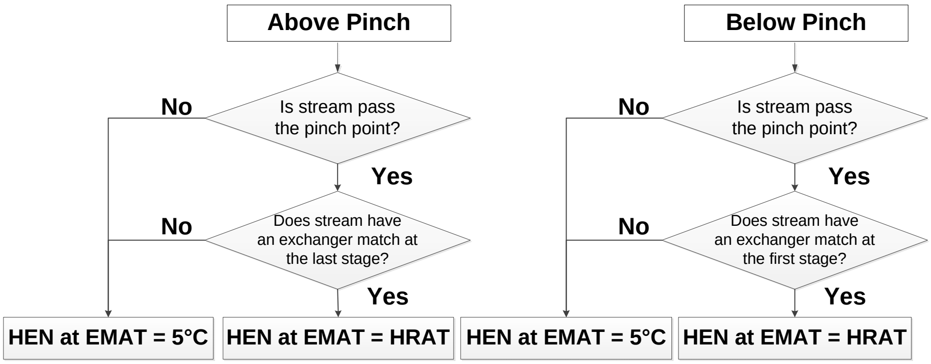


Figure 1: The HEN design algorithm of above-pinch and below-pinch HEN.

2.3 Screening step using MILP model

The retrofitted HENs obtained from the previous step are screened using MILP model to reduce the number of exchangers. Preliminary cost calculations of all designs are obtained and compared to costs from the previous step, and the most economical design is selected as the optimal topology for further validation.

2.4 Validation step by PRO/II

The HEN results obtained from the previous step are simulated to validate each design. This validation performs the total energy consumption of each crude type and exchanger area of each design.

2.5 HEN re-sequence step

After the validation step, the existing exchangers can be reused in this step with the same streams matching and also with small added or removed area. The re-sequence of exchangers results in the optimal HEN with the retrofit structure.

3. Case study

This work studies the HEN retrofit of crude preheat train of the simulated CDU with preflash drum as illustrated in Figure 2 with 9 existing process-process exchangers, 8 cooling utility exchangers, 3 heating utility exchangers, and 11 streams (8 hot streams and 3 cold streams). Three different crudes classified by their density into light, medium, and heavy crude are used for operating periods of 100, 150, and 100 days per annum.

The topology of the existing HEN is shown in Figure 3 with 149,188 MJ/h and 315,396 MJ/h of cold and hot utility consumption, respectively. Stream properties of all crude types are shown in Table 1, while the existing process-process exchangers and utility exchangers are displayed in Table 2. The CDU operates 350 working days per annum as an assumption with a project life of 5 years and 10% annual interest. Hot and cold utility costs are 0.4431 and 0.0222 cent/MJ, respectively. For the criteria of modifications, the existing shells can be reduced and added with maximum values of 50% and 20% of the existing area, respectively, with a maximum area per shell of 5,000 m^2 and a maximum number of shells per exchanger of 4. The objective of this model is to maximize NPV. The costs of area adjustment of exchanger are shown in Equations 1-4. The splitting cost is $20,000 per unit.

Exchanger ($) = 26,460 + [389×Area ($m^2$)] (1)

Area addition ($) = 13,230 + [389× Added Area (m^2)] (2)

Area reduction ($) = 13,230 + [0.5× Reduced Area (m^2)] (3)

New shell ($) = 26,460 + [389×Area of shell (m^2)] (4)

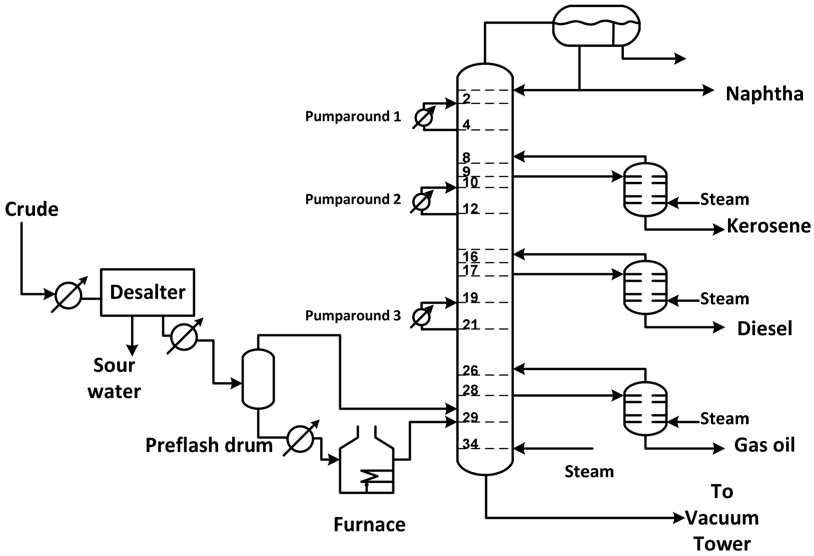


Figure 2: The existing crude distillation unit with preflash drum.

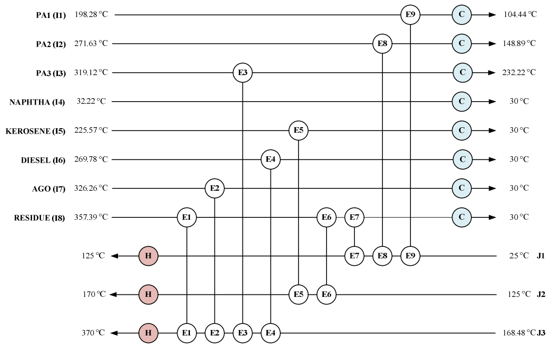


Figure 3: The existing HEN.

Table 1: Stream properties

Stream	Light crude				Medium crude				Heavy crude			
	FCp kW/ °C	T_{in} °C	T_{out} °C	h kW/m^2°C	FCp kW/ °C	T_{in} °C	T_{out} °C	h kW/m^2°C	FCp kW/ °C	T_{in} °C	T_{out} °C	h kW/m^2°C
I1	121.02	201.17	104.44	1.293	125.28	198.28	104.44	1.092	132.07	193.31	104.44	1.075
I2	69.91	274.71	148.89	1.318	71.80	271.63	148.89	1.235	74.03	267.77	148.89	1.221
I3	98.60	321.17	232.22	1.298	101.36	319.12	232.22	1.270	104.43	316.69	232.22	1.270
I4	105.22	32.22	30	1.058	91.92	32.22	30	1.253	70.57	32.22	30	1.309
I5	67.76	234.40	30	1.395	56.28	225.57	30	1.394	46.81	221.36	30	1.393
I6	49.64	273.17	30	1.423	34.77	269.78	30	1.431	29.33	263.57	30	1.438
I7	59.98	326.40	30	1.343	41.91	326.26	30	1.413	32.46	322.00	30	1.419
I8	135.33	341.73	30	0.892	210.12	357.39	30	0.888	268.65	353.52	30	0.826
J1	380.57	25	125	0.654	387.57	25	125	0.652	392.24	25	125	0.651
J2	434.32	125	170	0.632	443.70	125	170	0.630	449.76	125	170	0.630
J3	585.63	166.64	370	0.788	587.80	168.84	370	0.782	555.77	167.81	370	0.780

Table 2: Existing process-process exchangers and utility exchangers.

Process Exchanger	Area (m^2)	Heat Load (kW)		
		Light	Medium	Heavy
E1	1218	18866	29963	33546
E2	1035	9229	6574	5021
E3	75	4231	4223	4240
E4	435	5737	3894	3125
E5	485	6094	4354	3291
E6	484	8827	11906	13948
E7	461	6914	10888	13639
E8	142	8796	8697	8644
E9	182	9616	9151	8962

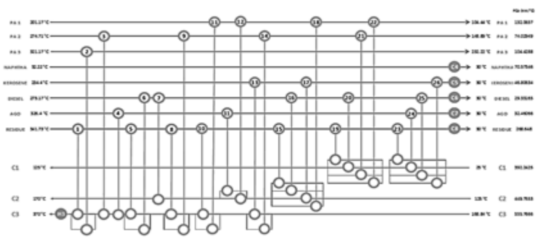
Utility Exchanger	Area (m^2)	Heat Load (kW)		
		Light	Medium	Heavy
H1	219.40	12731	10022	7979
H2	89.07	4623	3707	3000
H3	2024.50	81029	73587	66438
C1	35.80	2091	2605	2775
C2	1.34	0.61	115	157
C3	20.83	4540	4586	4581
C4	34.09	234	204	157
C5	177.51	7756	6654	5666
C6	131.17	6335	4443	3725
C7	168.26	8549	5842	4458
C8	861.31	7579	16035	25781

4. Results and discussion

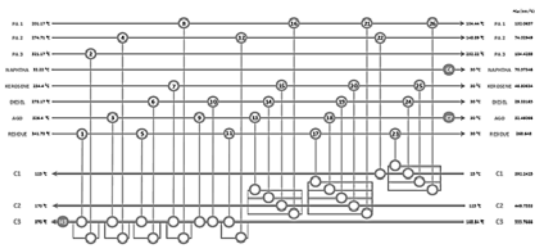
NPV is considered as an economic parameter used to select the optimal retrofitted HEN design which gives the highest one. The retrofit potential program targets the optimum HRAT and pinch temperature of each crude type as shown in Table 3. The optimum HRAT of each crude type is used as a constraint for formulating HEN. Retrofitted HENs of each crude base design are illustrated in Figure 4.

Table 3: Optimum HRAT and pinch temperature.

Crude Type	Current HRAT	Optimum HRAT	Hot Pinch Temperature	Cold Pinch Temperature
Light	91.9 °C	8 °C	33 °C	25 °C
Medium	87.75 °C	11.8 °C	180.64 °C	168.84 °C
Heavy	87.87 °C	11.8 °C	179.61 °C	167.81 °C



(a)



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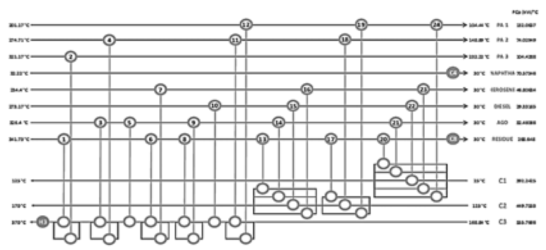
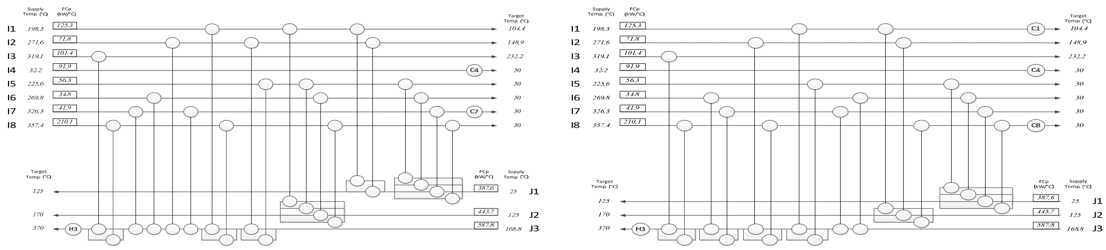


(c)

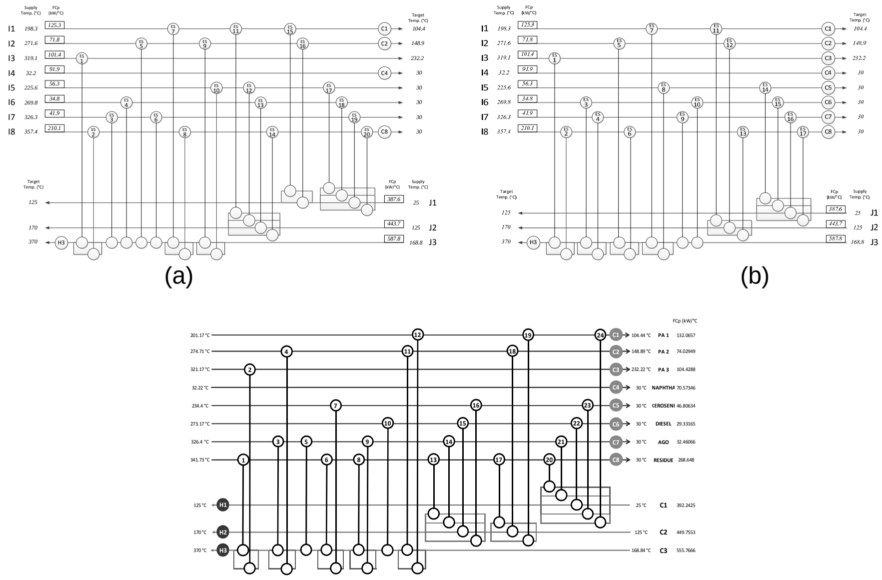
Figure 4: Retrofitted designs of (a) Light crude base, (b) Medium crude base, and (c) Heavy crude base.

Retrofitted designs from the previous step are screened by MILP model to reduce exchangers used with slight energy consumption change. This reduction of exchangers affects heat exchanger area and also capital cost. Preliminary costing is required to achieve the most economically attractive retrofitted HEN of each crude base by screening step and comparison with results from the previous step. Screening of light and medium crude base retrofitted design as shown in Figures 5a and 5b, respectively, provides a more economical HEN, while retrofitted design of heavy crude base after screening step is less economical. From this step, retrofitted design of light and medium crude base with screening step and retrofitted design of heavy crude base before screening step are selected for validating by Pro/II. Validated retrofitted designs of all crude bases are shown in Figure 6.



(a) (b)

Figure 5: Screening of retrofitted designs of (a) Light crude base and (b) Medium crude base.



(a) (b) (c)

Figure 6: Validated retrofitted designs of (a) Light crude base, (b) Medium crude base, and (c) Heavy crude base.

Overall hot and cold utility of retrofitted HEN for each crude base is validated by commercial simulation software; Pro/II. Consequently, the total exchanger area of each crude base design is calculated. Process-process exchanger areas and utility exchanger areas of each crude base design are shown in Tables 4 and 5, respectively. Following the re-sequence step, total cost and NPV are calculated as displayed in Table 6.

Table 4: Process-process exchanger areas of all crude base designs.

Light crude base				Medium crude base				Heavy crude base			
Exchanger number	Area (m²)	Exchanger number	Area (m²)	Exchanger number	Area (m²)	Exchanger number	Area (m²)	Exchanger number	Area (m²)	Exchanger number	Area (m²)
ES1	3174.5	ES12	549.7	ES1	1059.9	ES10	103.0	ER1	5689.6	ER13	7.3
ES2	1439.3	ES13	270.1	ES2	1937.5	ES11	2375.2	ER2	3039.2	ER14	75.9
ES3	370.2	ES14	287.5	ES3	239.9	ES12	295.2	ER3	249.4	ER15	299.8
ES4	312.0	ES15	675.3	ES4	282.4	ES13	907.2	ER4	438.5	ER16	317.0
ES5	626.7	ES16	416.6	ES5	429.5	ES14	508.0	ER5	149.2	ER17	1392.9
ES6	92.5	ES17	78.8	ES6	615.6	ES15	509.4	ER6	3099.0	ER18	186.4
ES7	929.3	ES18	572.0	ES7	377.7	ES16	803.4	ER7	380.8	ER19	715.7
ES8	420.0	ES19	837.8	ES8	167.0	ES17	1908.3	ER8	1225.4	ER20	1337.0
ES9	178.7	ES20	753.0	ES9	26.9			ER9	166.1	ER21	412.8
ES10	184.2	ES21	2397.7					ER10	228.0	ER22	407.2
ES11	108.0							ER11	306.0	ER23	706.0
								ER12	31.1	ER24	254.2

Table 5: Utility exchanger areas of all crude base designs.

Light crude base	
Exchanger number	Area (m^2)
CR1	57.7
CR2	5.3
CR4	33.2
CR8	726.2
HR3	1,467.5

Medium crude base			
Exchanger number	Area (m^2)	Exchanger number	Area (m^2)
CR1	35.2	CR6	45.4
CR2	20.0	CR7	61.6
CR3	0.6	CR8	565.5
CR4	33.2	HR3	1,526.0
CR5	76.6		

Heavy crude base			
Exchanger match	Area (m^2)	Exchanger match	Area (m^2)
CR1	9.3	CR7	89.2
CR2	2.5	CR8	529.7
CR3	5.3	HR1	45.0
CR4	33.3	HR2	59.7
CR5	66.3	HR3	1,397.5
CR6	60.5		

Table 6: Cost summary.

	Base case	**Retrofit Design**		
		Light crude base	Medium crude base	Heavy crude base
No. of new exchangers	-	17	12	23
No. of existing exchangers used	-	10	5	12
Area of all exchangers	8,280	16,964	14,910	17,725
Investment cost for 5 years life time ($)	-	5,625,594	4,935,881	8,289,067
Heating Utility (MJ/a)	2,650,534,397	1,532,422,456	1,493,504,984	1,376,106,923
Cooling Utility (MJ/a)	1,253,746,794	346,140,418	296,368,173	234,323,891
Energy saving ($/a)	-	3,698,938	4,091,922	5,873,300
No. of splits	0	9	9	14
Splitting cost ($)	-	180,000	180,000	280,000
NPV ($)	-	8,396,290	10,575,722	13,975,361

5. Conclusions

Retrofit of HEN by combining the pinch design method and mathematical programming yields positive NPV designs. Optimum HRAT is targeted by the pinch design method, while HEN calculations on complex problems under designed constraints are performed by powerful mathematical programming. Screening of retrofitted design is executed for reducing the number of exchangers. HEN validation by commercial simulation software is performed next, resulting in correction of total utility consumption and exchanger areas. The re-sequence step indicates the investment cost of all possible designs. The optimum design is selected from one with highest economic parameter; NPV. From this case study consisting of three types of crude, the heavy crude base design is the most profitable HEN with maximum NPV of $13,975,361 and total utility saving of 41.2%.

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