RETROFIT OF CRUDE PREHEAT TRAIN WITH MULTIPLE TYPES OF CRUDE

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Keywords: Heat Exchanger Network (HEN), Pinch analysis, Mixed integer linear programming, Stage model, Retrofit.

Abstract: This study explores the retrofitting of the crude preheat train of a crude distillation unit (CDU) processing two types of crude--light and heavy--for a period of 200 and 150 days per year, respectively, with the aim of finding the optimal design that would yield the highest net present value (NPV). A mathematical programming model using GAMS software of heat exchanger network (HEN) called stage model (Zamora and Grossmann, 1996) is applied to carry out the retrofit. The base case CDU is simulated by PRO II software. Using pinch analysis, the composite curves show the retrofit potential of base cases with light and heavy crude. The 10-stage model generates six retrofit designs--Designs 1, 2, 3, 4, 5, and 6--of which Designs 1, 2, and 3 are suitable for light crude and Designs 4, 5, and 6 are suitable for heavy crude. Using a graphical technique of searching for optimization with maximized NPVs of all designs, it is shown that Design 2 is the optimal retrofit design processing both types of crude, yielding the highest NPV of $11,529,511 for a 5-year lifetime and resulting in furnace duty saving of 32%.

1 INTRODUCTION

The crude distillation unit (CDU), as shown in Figure 1, is one of the largest energy-consuming units in a refinery. It has a complex heat exchanger network (HEN) of crude preheat train which transfers heat from hot-product and pump-around streams to preheat crude before it enters the CDU, resulting in energy saving in crude furnace and coolers of CDU. For this study, PRO II software is used to simulate base case CDU operated under Arabian light (light crude) and Bacha quero (heavy crude) with different distillation curves (Figure 2). The volumes of crude products from CDU of light and heavy crude are found in Table 1. CDU of light and heavy crude of 5000 barrels/hr consumes different steam and condenser duties (Table 2).
This work focuses on retrofitting the base case crude preheat train of light and heavy crude by using a graphically searching technique with n-stage model.

2 LITERATURE SURVEY

In the 1970s, pinch technology, or process heat integration, which aids the design of an efficient HEN by the use of composite curves (T-Q diagram), as shown in Figure 3, was developed. This technology has enabled a theoretical approach to design an optimal HEN and find retrofit potential of the process. The composite curves consist of hot and

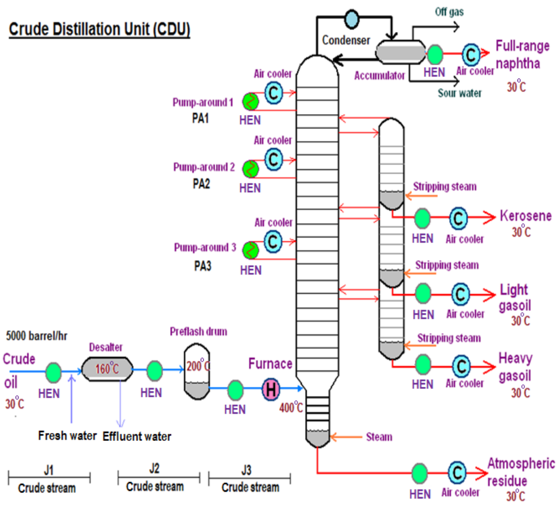

Figure 1: Crude distillation unit.

Siemanond K. and Kosol S..
RETROFIT OF CRUDE PREHEAT TRAIN WITH MULTIPLE TYPES OF CRUDE.
DOI: 10.5220/0003577203030308
In *Proceedings of 1st International Conference on Simulation and Modeling Methodologies, Technologies and Applications* (SIMULTECH-2011), pages 303-308
ISBN: 978-989-8425-78-2

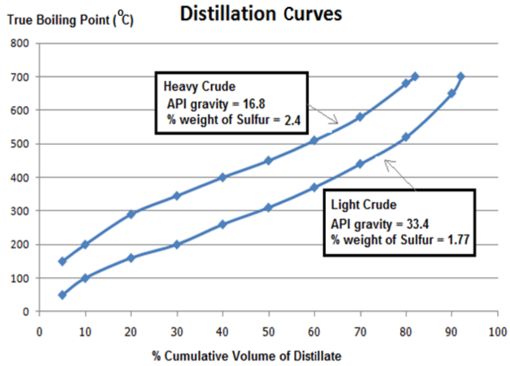

Figure 2: Distillation curves of crude.

Table 1: Products from light and heavy crude.

Products	Products Cut Range (°C)	Volume of Products from Light Crude at 30°C	Volume of Products from Heavy Crude at 30°C
Naphtha	0 - 171 °C	23 %	6 %
Kerosene	171 - 271 °C	18 %	10 %
Gasoil	271 - 473 °C	28 %	22 %
Residue	473°C +	31 %	62 %

Table 2: Steam and condenser duties of CDU.

	Energy Consumption of CDU	
	with Light Crude Feed 5000 Barrels/hr	with Heavy Crude Feed 5000 Barrels/hr
Steam and Side-stripping Steam Duty	7.673 MMW	8.07 MMW
Condenser Duty	62.3 MMW	13.9 MMW

cold composite lines presenting the relationships between temperature (T) and heat content (Q) for heat sources and sinks in the system. A pinch point of two lines indicates a heat recovery approach temperature (HRAT) or a thermodynamic constraint on heat exchange. Shifting the cold composite curve to the left improves heat recovery, or energy saving, by increasing the heat-exchanger area.

The retrofit technique by Tjoe and Linnhoff (1986) using pinch technology or thermodynamic method applies targeting procedures to energy-area tradeoffs which subsequently translate into investment savings plots. Yee and Grossmann (1990) proposed assignment-transshipment models for structural modifications and a two-stage approach. Ciric and Floudas (1988) proposed a retrofit strategy using a decomposition method. Briones and Kokossis (1998) used the hypertargets or conceptual programming approach for retrofitting industrial heat exchanger networks.

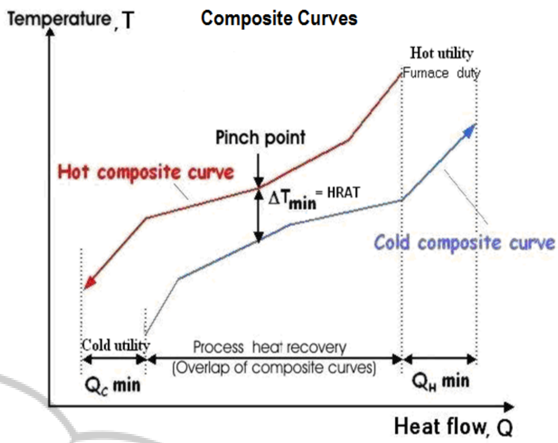

Figure 3: Composite curves.

3 N-STAGE MODEL

The stage model developed by GAMS software is based on the stage-wise superstructure representation proposed by Zamora and Grossman (1996), as shown in Figure 4. Within each stage of superstructure, possible exchanger between any pair of hot and cold streams can occur. Heater and coolers are placed at the end of cold and hot streams, respectively. The objective function of the model is to minimize the duties of heater, cooler and number of exchangers under the constraint functions of energy balance, thermodynamics, logical, and retrofit constraints. The target temperatures and flow rates of hot and cold streams are fixed and the stage model will design HEN into n stages with the minimum utility usages and number of exchangers for fixed EMAT (Exchanger Minimum Approach Temperature).

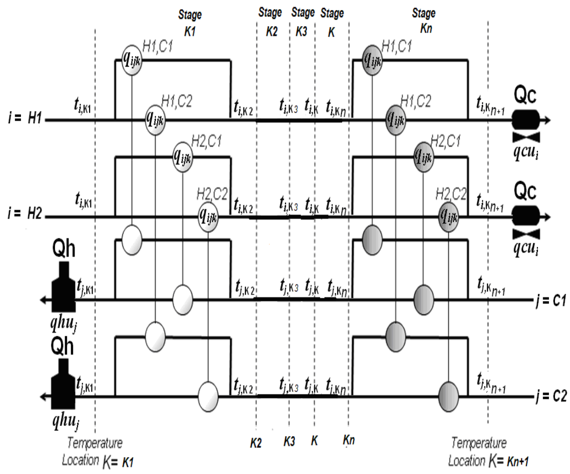

Figure 4: n-stage model structure.

Generally, the number of stages in the superstructure is set equal to the maximum cardinality of the hot and cold sets of streams, although sometimes it is necessary to increase the number of stages to allow designs with minimum energy consumption. The purpose of the retrofit model is to minimize the number of exchangers under constraint functions of energy balance, thermodynamics, logical constraint and retrofit constraint. The retrofit constraint is shown in equation (1):

$$\sum_{i=1}\sum_{j=1}\sum_{k=1} Zijk \le 1 \quad (1)$$

where Zijk is a binary variable of existing exchanger matches between hot (i) and cold (j) streams at stage k. This constraint helps retrofit HEN by keeping base case exchangers in the same location in the retrofit design.

4 RESULTS AND DISCUSSION

4.1 Base Case

This case study focuses on retrofitting a base case crude preheat train of light and heavy crude for 200 and 150 days per year, respectively. The base case consists of eight hot product streams (PA1, PA2, PA3, Naphtha, Kerosene, Light Gasoil, Heavy Gasoil, and Residue), three cold crude streams (J1, J2, and J3), as seen in Figure 1, and eight process exchangers (E1, E2, E3, E4, E5, E6, E7, and E8) with an area of 5621.97 m^2, as shown in Figures 5 and 7. The base case crude preheat train is operated under light and heavy crude for 350 working days per year.

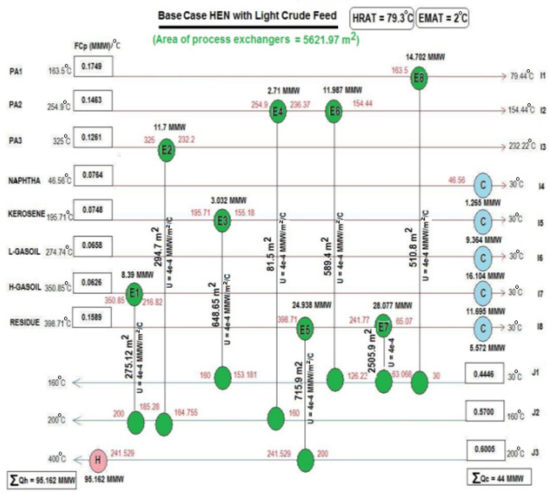

Figure 5: Base case HEN with light crude feed.

4.1.1 Base Case of Light Crude

The structure of base case crude preheat train operated under light crude for 200 days per year for the lifetime of 5 years is shown in Figure 5. It consumes furnace and cooler duties of 95.162 and 44 MMW, respectively, at HRAT = 79.3°C.

The composite curves of this base case, as shown in Figure 6, show a retrofit potential, meaning retrofit of this base case to reduce furnace and cooler duties is possible.

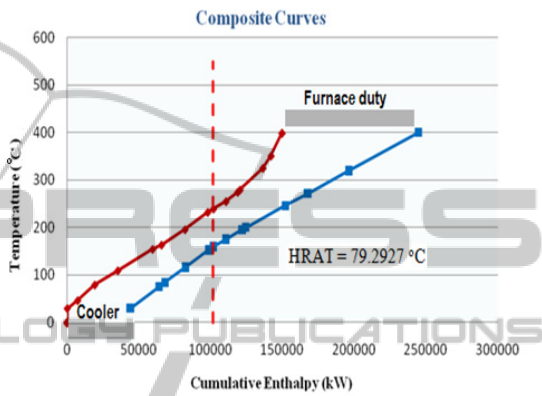

Figure 6: Composite curves of base case of light crude HEN.

4.1.2 Base Case of Heavy Crude

The structure of base case crude preheat train operated under heavy crude for 150 days per year for a lifetime of 5 years is shown in Figure 7. It consumes furnace and cooler duties of 91.4 and 96.37 MMW, respectively, at HRAT = 113.6°C.

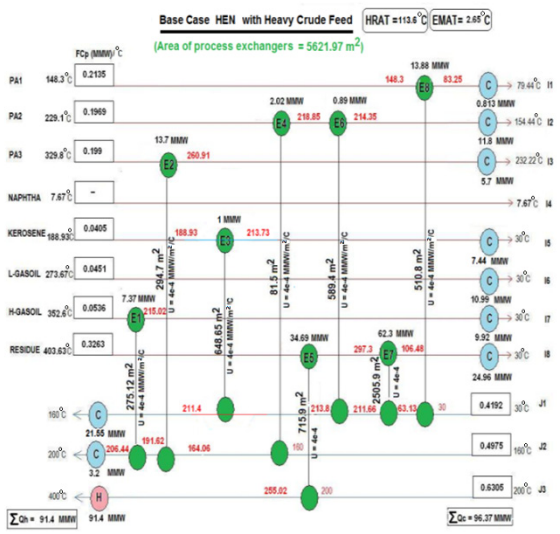

Figure 7: Base case HEN with heavy crude feed.

The composite curves of this base case, as shown in Figure 8, also show a retrofit potential.

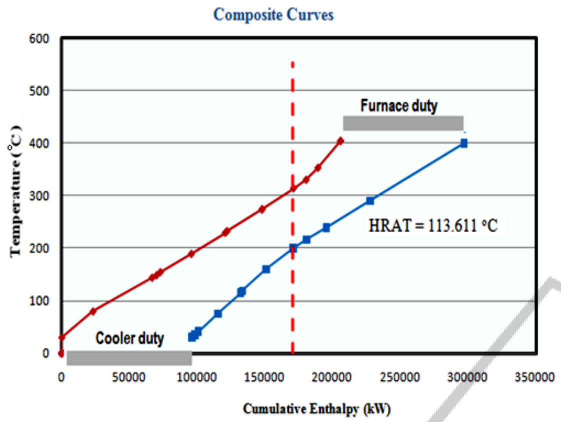

Figure 8: Composite curves of base case of heavy crude HEN.

The retrofit with 10-stage model is applied to the base-case HEN and gives six retrofit designs: Designs 1, 2, 3, 4, 5, and 6. Designs 1, 2, and 3 are suitable for light crude for 200 days per year while Designs 4, 5, and 6 are suitable for heavy crude for 150 days per year.

4.2 The Optimal Retrofit Case

The base case of light crude is retrofitted by 10-stage model using GAMS, generating six retrofit designs at different HRATs, selectively, with different furnace duty (hot utilities) and cooler duty (cold utilities), as shown in Tables 3, 4, and 5.

Table 3: Six retrofit designs with exchanger area.

HEN Design	Overall Area of Process Exchangers (m2)	Number of Process Exchangers
Base Case	5622	8
Design 1 with repiping	24253	12
Design 2 with repiping	16126	11
Design 3 with repiping	10727	9
Design 4 with repiping	15246	9
Design 5 with repiping	9742	7
Design 6 with repiping	4278	6

Table 4: Six retrofit designs for light crude.

HEN Design	HEN with Light Crude for 200 Days per Year		
	HRAT (°C)	Hot Utility (MMW)	Cold Utility (MMW)
Base Case	79.3	95.162	44
Design 1 with repiping	19.56	67.162	16
Design 2 with repiping	27.43	71.162	20
Design 3 with repiping	48.73	81.162	30
Design 4 with repiping	83.52	97.111	46.365
Design 5 with repiping	103.36	107.66	56.495
Design 6 with repiping	110.97	117.79	59.88

Table 5: Six retrofit designs for heavy crude.

HEN Design	HEN with Heavy Crude for 150 Days per Year		
	HRAT (°C)	Hot Utility (MMW)	Cold Utility (MMW)
Base Case	113.61	91.4	96.37
Design 1 with repiping	41.63	48.5	53.26
Design 2 with repiping	50.01	53.495	58.49
Design 3 with repiping	64.49	63.48	67.52
Design 4 with repiping	40.46	47.57	52.528
Design 5 with repiping	63.88	62.185	67.143
Design 6 with repiping	88.36	76.8	81.579

The net present value (NPV) is based on future cash flows for a certain number of years, n, and a specific annual interest rate. The NPV is calculated as follows:

$$NPV = \sum_{i=1}^{n \text{ years}} \left(\frac{\text{Utility saving cost}_i}{(1 + \text{Annual interest rate})^i} \right) - \text{Total Investment cost} \quad (2)$$

Table 6 shows the NPV for each retrofit design.

Table 6: NPV of six retrofit designs.

HEN Design	Hot Utility Saving (%)	Cold Utility Saving (%)	Total Investment Cost ($)	NPV ($) for 5-Year Life Time
Base Case	0	0	0	0
Design 1 with repiping	37	24	7850012	10493294
Design 2 with repiping	32	48	4450209	11529511
Design 3 with repiping	21	36	2490492	8169180
Design 4 with repiping	19	17	4640917	4778489
Design 5 with repiping	6	18	3456974	-587666
Design 6 with repiping	-7	5	1271623	-4732723

The economic data including utility and investment costs for this retrofit case are as follows.

The lifetime of this retrofit project is 5 years and the annual interest rate is 10% (350 working days per year). The cost of hot and cold utilities are 0.4431 and 0.0222 cents per megajoule, respectively. The maximum exchanger area added to and removed from existing exchanger shells are 10% and 40%, respectively. The maximum limit of area per shell is 5,000 m^2 and one exchanger can contain up to 4 shells. The constraint of this retrofit case is that there is no splitting on hot streams. The cost for stream splitting and repiping is $20,000. The investment costs of area are shown in equation (3), (4), (5), and (6).

$$\text{Exchanger (\$)} = 26{,}460 + [389 \times \text{Area (m}^2)] \quad (3)$$

$$\text{Area addition (\$)} = 13{,}230 + [857 \times \text{Area}_{added}(\text{m}^2)] \quad (4)$$

$$\text{Area reduction (\$)} = 13{,}230 + [5 \times \text{Area}_{reduced}(\text{m}^2)] \quad (5)$$

$$\text{New shell (\$)} = 26{,}460 + [857 \times \text{Area}_{shell}(\text{m}^2)] \quad (6)$$

The optimal retrofit design (Retrofit Design 2) from the graphically searching technique is the one with HRAT = 27.43°C, giving the highest NPV of

$11,529,511 for a lifetime of 5 years, as shown in Figure 9.

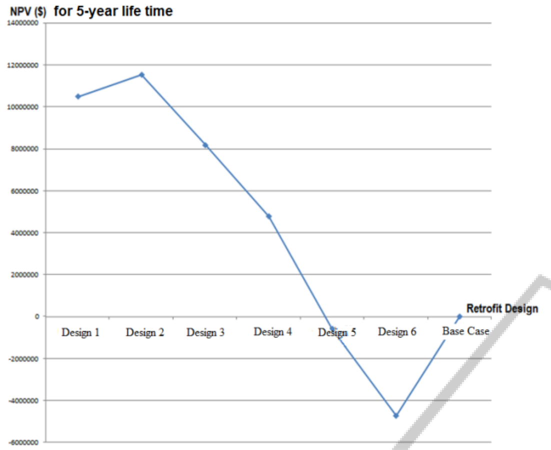

Figure 9: Graphical technique for searching optimization.

Details of Retrofit Design 2 are provided in Table 7 and Figures 10 and 11. It will be applied to handle light and heavy crude, giving different furnace and cooler duties.

Table 7: Exchanger details of Retrofit Design 2.

Heat Exchanger	Base-Case Area (m²)	Heat Load after Retrofit (kW)	Retrofit Area (m²)	Area Change (m²)	Area Change Change	
E1	275.1361272	1696	451.7080789	176.5719517	64%	Area Addition (new shell)
New4	294.7574278	3336	62.85021006	-231.9072178	-79%	New exchanger
E3	648.2008987	11797	1370.347204	722.1463052	111%	Area addition (new shell)
E4	81.56044336	10412	1629.884525	1548.324082	1898%	Area addition (new shell)
E5	715.8833888	31257	2761.007516	2045.124127	286%	Area addition (new shell)
E6	589.3756518	4286	959.962177	370.5865252	63%	Area addition (new shell)
E7	2507.04249	27013	4423.010594	1915.968105	76%	Area addition (new shell)
E8	510.8456792	14702	1341.708165	830.8624862	163%	Area addition (new shell)
New1	-	8363	877.2614398	-	-	New exchanger
New2	-	9318	1226.443202	-	-	New exchanger
New3	-	7356	658.6909704	-	-	New exchanger

	Hot Utility	Cold Utility
kW	71162	20000
$/yr	9535708	134265.6

Repiping ($)	20000
Splitting ($)	80000
Total investment ($)	4,450,208.652

Annualized invest. cost ($/yr)	1,173,953.83
Energy cost ($/yr)	9,669,973.60
Energy saving ($/yr)	3,377,118.72

5 CONCLUSIONS

The 10-stage model of HEN generates six retrofit designs of crude preheat train. Designs 1, 2, and 3 are suitable for light crude for 200 days per year, and Designs 4, 5, and 6 are suitable for heavy crude for 150 days per year. In comparing the NPV of the six designs, it is shown that the optimal retrofit design handling light crude for 200 days and heavy crude for 150 days per year is Retrofit Design 2, which gives the optimal NPV of $11,529,511 for a 5-year lifetime and results in 32% saving at the furnace.

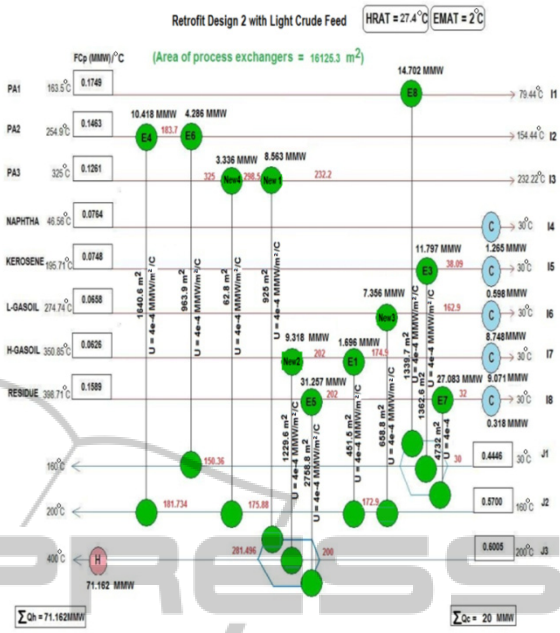

Figure 10: Design 2 with light crude feed.

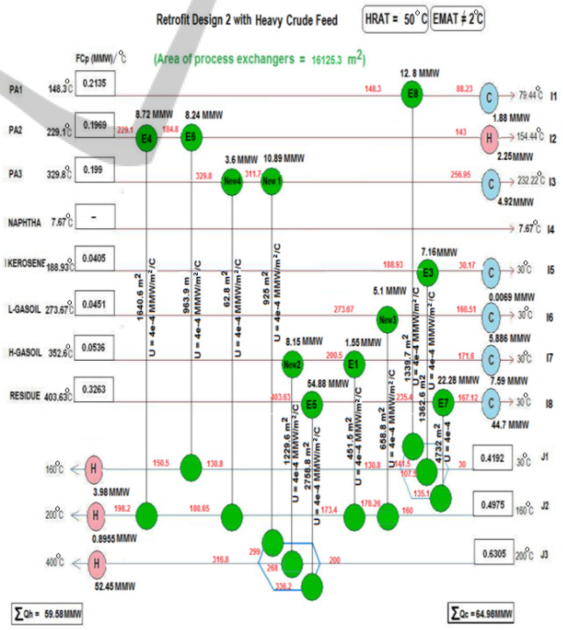

Figure 11: Design 2 with heavy crude feed.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Government Budget Bureau, the Petroleum and Petrochemical College, Chulalongkorn University, and the National Center of Excellence for Petroleum, Petrochemicals and Advanced Materials for funding support. The invaluable assistance of Prof. Miguel Bagajewicz for educating us in mathematical programming, GAMS, is also gratefully acknowledged.

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