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Retrofit of Crude Pre-Heat Train using MINLP Model under Non-Isothermal Mixing Assumption

Supiluck Koraviyotin[a], Kitipat Siemanond*[b]

[a]The Petroleum and Petrochamical College, Chulalongkorn University, 254 Phayathai Rd., Pathumwan, Bangkok 10330
[b]Center of Excellence on Petrochemical and Materials Technology, Soi Chulalong korn 12, Phayathai Rd., Pathumwan, Bangkok 10330, Thailand
kitipat.s@chula.ac.th

To enhance the energy recovery through heat integration, heat exchanger network synthesis (HENS) has been introduced for industrial processes in the last several decades. The systematic identification of retrofit designs of the existing complex network in industrial processes is case-dependent problem, especially crude oil atmospheric distillation systems. Therefore, retrofit design is one of the most challenging heat exchanger network (HEN) designs where no standard formulation deals with the fixed cost of topology changes. The revision of an existing HEN is more complex than the grassroots design. This work is to modify a mixed-integer nonlinear programming (MINLP) stage-wise model using commercial optimization software; GAMS, for retrofitting HEN where the main objective is to maximize profit calculated by energy saving subtract total investment cost of additional exchanger area, new exchanger, stream splitting and repiping. The proposed model overcomes the area trade-off restriction caused by the assumption of isothermal mixing and allows several matches located on a branch of each process stream. Dealing with the MINLP case, the initialization strategy is developed to find feasible starting point for the optimization problem resulting in generating more profitable HEN design compared to the published one from the literature.

1. Introduction

Revamping an existing plant is a difficult task and more complex than a new process design (Sieniutycz and Jeżowski, 2009). In recent years, the redesign of an existing network can often reduce the operating costs in a process. In addition, a network may require redesign when process modifications in the plant alter the conditions of the process streams (Yee and Grossmann, 1991). The major objectives of retrofit design are the reduction of utility use in the existing network, the full utilization of the existing heat exchangers, and the identification of the required structural modifications (Ciric and Floudas, 1990). The improved heat recovery for the heat exchanger networks (HENs) can be achieved through various retrofit techniques, including implementing intensified heat transfer techniques, adding additional heat transfer area, installing new exchangers, and reconfiguring heat recovery structure - e.g. repiping (Pan al., 2013). Physical heat exchanger retrofit is achieved by either structural or parameter changes. In general, structural modifications can be grouped into four broad categories. New exchangers can be purchased, the area of existing exchangers can be increased or decreased, streams can be repiped, and existing exchangers can be reassigned from one match to another. When formulating and solving heat exchanger network retrofit optimization, logical conditions and binaries are required causing the difficulties on structural changes. The later ones mean the increase or decrease of surface area and also the addition of new splitters, mixers and heat exchangers. Due to the two sequential steps of Pinch design method by Linnhoff and Hindmarsh (1983), which consist of the pinch matching step to do vertical heat transfer matching around Pinch Point and the relaxation step to reduce exchanger number, the heat-integration study of Yee and Grossmann (1990) addressed one step to design vertical and/or criss-cross heat transfer matches simultaneously using stage-wise mathematical programming model. Siemanond and Kosol (2013) proposed Pinch design approach where Above-and-Below-Pinch HEN was optimized for the utility

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consumption levels of any HEN by applying stage-wise mathematical programming model , resulting in less computational time to design HEN because of heuristics of Pinch as shown in the work of Angsutorn, Siemanond and Chuvaree (2013). To achieve a rigorous optimization of the structure, sizes of heat exchangers and utility usage, mathematical programming methods is used to find the cost optimal network structures among the various structures. Björk and Nordman (2005) modified the Synheat model using superstructure. It limits more feasible region than the original Synheat model did where the constraints in modified model are used to ensure that existing heat exchanger is used at once. To the large-scale problems, the authors, therefore, relied on a hybrid solution strategy. Recently, Bagajewicz et al. (2013) proposed Heat Integration Transportation Model (HIT) for retrofitting HEN of crude units which is mathematical programming-based MILP model to simultaneously take into account the trade-offs between energy saving and capital costs. The model uses the concept of transportation of heat from a hot stream temperature interval to a cold stream temperature interval where the temperature difference is allowed. Since all equations in model are linearized, the linear solver can be applied. Amongst various types of applications of HEN, crude oil atmospheric distillation unit in the petroleum refineries case is one of the most challenging. Therefore, the objective of this work is retrofitting the existing HEN of Crude Distillation Units (CDU) to reduce the recent utility consumption and maximize Net Present Value (NPV). This work proposes the modified stagewise superstructure model by Yee and Grossmann (1990). The model is MINLP often involving highly non-linear and non-convex terms to account for the non-isothermal mixing and allow the multiple exchanger matches on each of branch stream. To provide good initial values for simultaneous retrofit of HENs, a two-step strategy is implied. The effective model formulations and effective initialization strategy are applied to CDU case-study.

2. The modified and extended Synheat model

To eliminate the restriction of the area trade-offs between the exchangers and the overestimation of the area cost, the original stage-wise superstructure of Yee and Grossmann (1990) is modified and extended as depicted in Figure 1. According to the omission of isothermal mixing assumption from the stagewise model, the non-linear and non-convex terms are introduced to the model accounting for the varieties of heat capacity flowrate of branch stream and outlet temperature from exchanger.

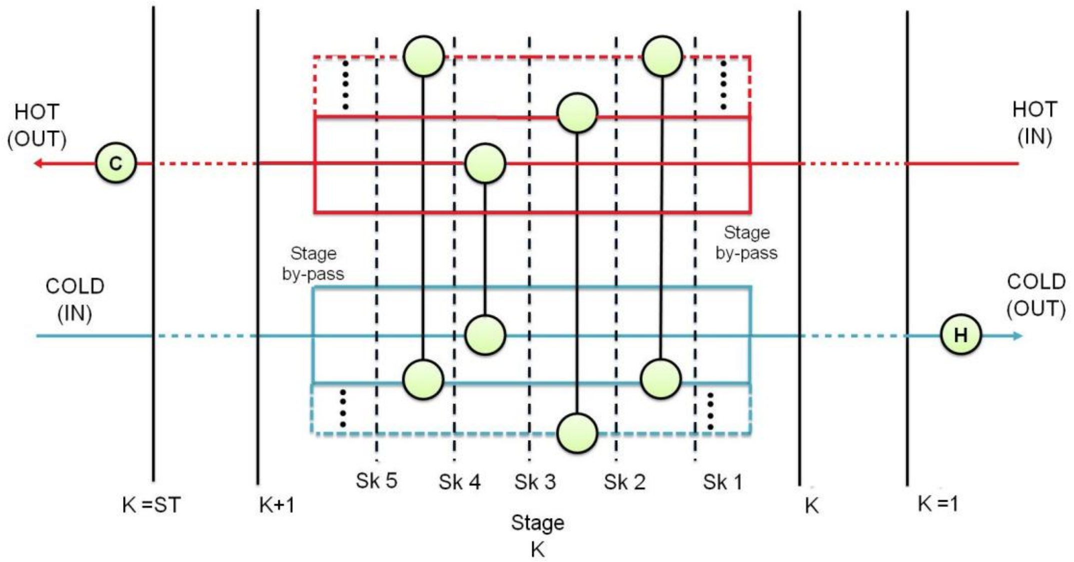

Figure 1: The grid diagram (Linnhoff and Hindmarsh, 1983) representing modified and extended stage-wise superstructure of Yee and Grossmann (1990) with non-isothermal mixing allowing several exchanger matches per branch stream

As depicted in Figure 1, any branch stream can pass through the multiple exchangers. Each of hot and cold streams split into a number of branch streams containing many temperature intervals of sub-stages; SKs, in stage; K. The potential exchangers are placed between hot and cold stream at each sub-stage SK; whereas, a bypass stage does not allow the branch stream to recovery heat. At last sub-stage; SK of each stage; K, branch streams merge to form the main stream. Finally, the final temperature of each main process stream is targeted by using utility at last main stage K. The extra set of temperature variables in each sub-stage for a hot stream in the hot end of exchanger or for a cold stream in the cold end of exchanger is introduce into the model and the outlet temperatures of each branch stream can be varied at last sub-stage SK to overcome the area trade-off restriction caused by the assumption of isothermal mixing.

3. Solution strategy

The retrofit model is developed from the grass-roots model. The additional sets of constraints are added into the grassroots model to consider the network modifications. Therefore, the model consists of 2 sets of equations; the synthesis and retrofit equations. The objective of grassroots design is to minimize the total cost, which includes the utilities cost (i.e., operating cost) and the investment cost of the HEN. The goal for retrofit case is to maximize the heat integration among process streams or reduce utilities usage and therefore maximize the NPV calculated by the energy saving subtracted by the investment cost. Although the modified and extended Synheat model looks promising, the problem of the model occurs when it handles the effect of high non-convexities which prevent model from obtaining the feasible solution. This difficulty needs to be overcome by applying the effective initialization strategy. This strategy consists of two main steps; initialization and retrofitting steps as shown in Figure 2.The initialization steps are divided into two steps. The first initialization step is to find the minimum number of exchangers by fixing the number of branch flow stream and using the MILP solver. The initialized variables consist of continuous variables of heat load distribution, calculated area, number of exchangers and total annual cost calculated by fixed cost of exchanger and area addition. The second initialization step formulates the MINLP model to minimize total annual cost composing of capital and operational expenses. After initial HEN is provided, the retrofit step is done by using MINLP with the objective function of maximum NPV.

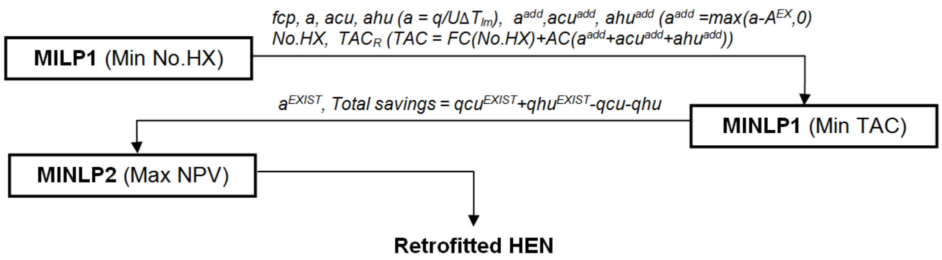

Figure 2: The HEN retrofit strategy

4. Example

Figure 3 presents the original HEN for the crude distillation unit (CDU) from Siemanond and Kosol (2012) consisting of 13 streams (10 hot and 3 cold process streams) and 18 exchangers (6 process exchangers, 3 hot utility exchangers and 9 cold utility exchangers). The original HEN uses two types of hot utility and three types of cold utility. Branch stream does not exist in the original HEN. Cost, film coefficient, supply and target temperature of utilities are shown in Table 1. The film coefficient of stream is shown in Table 2. The project life is 5 years with 67,964 kW of hot utility and 75,051kW of cold utility consumption per year of original HEN. Modifications in the HEN account for new exchanger addition and area addition or reduction to existing exchangers. The limitation of additional and reduction area are 10 % and 40 % of existing exchanger area for all exchanger, except the two exchangers (HX5 and HX12). The limitation values of additional and removed area of H5-C1 match for both HX5 and HX12 are 20 % and 30 %. The maximum area per shell is 5,000 m^2 and the maximum number of shells per exchanger is 4. The fixed cost of branch streams is $ 20,000 per branch. Eq(1) to (4) calculate the total cost of new exchanger, area reduction, area addition, and new shells made to existing exchangers.

$$\text{Exchanger cost (\$)} = 26{,}460 + [389 \times \text{Area} (m^2)] \quad (1)$$

$$\text{Additional area cost (\$)} = 13{,}230 + [389 \times \text{Area}^{addition} (m^2)] \quad (2)$$

$$\text{Reduction area cost (\$)} = 13{,}230 + [0.5 \times \text{Area}^{reduction} (m^2)] \quad (3)$$

New shell cost ($) = 26,460 + [389 × $\text{Area}^{\text{shell}}$ (m^2)] (4)

5. Results and discussion

The results of the retrofitted exchanger area compared to original exchanger area are summarized in Table 3. The retrofitted topology is shown in Figure 4 and 5. The retrofitted HEN consists of 14 exchangers from existing network and four new exchangers (exchangers No. 19, 20, 21, and 22) added.

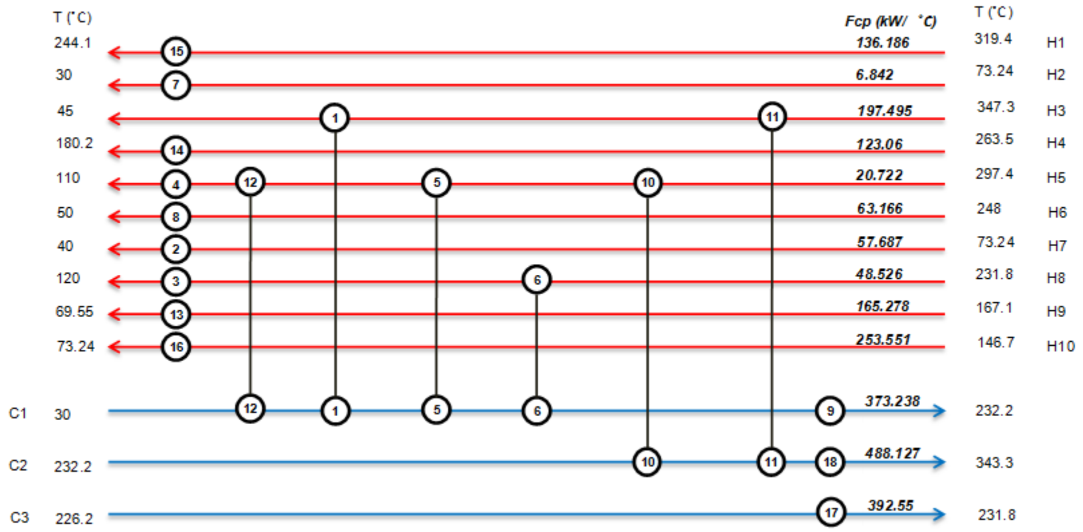

Figure 3: The Grid Diagram of the original HEN from Siemanond and Kosol (2012)

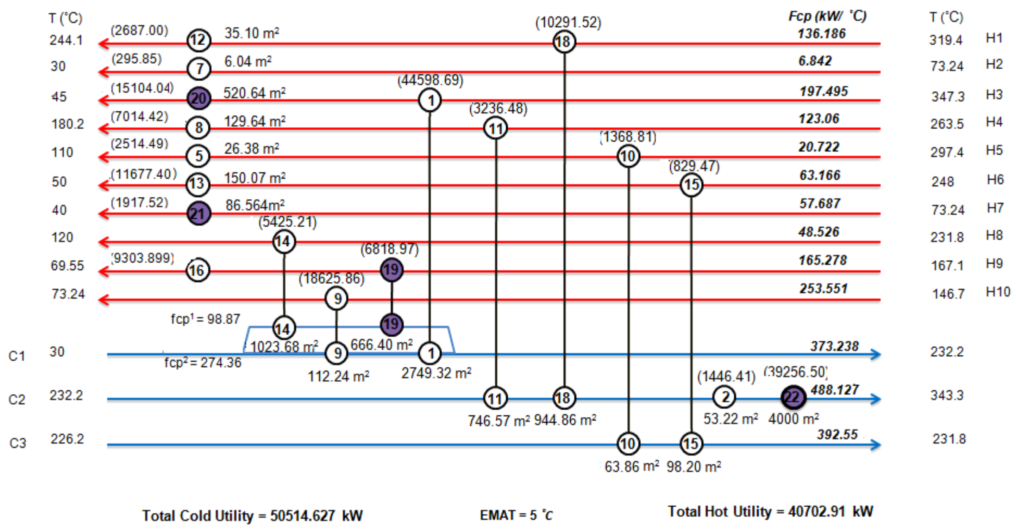

Figure 4: The Grid Diagram of retrofit case from our work

Table 1: Cost, film coefficient, supply and target temperature of utilities

Hot/Cold Utility	Cost/y ($/kJ)	*h*, film coefficient (kW/m^2/°C)	Tin (°C)	Tout (°C)
HU1	71.09	6	250	249
HU2	134	0.111	1,000	500
CU1	6.713	3.75	20	25
CU2	23.4	6	124	125
CU3	45.9	6	174	175

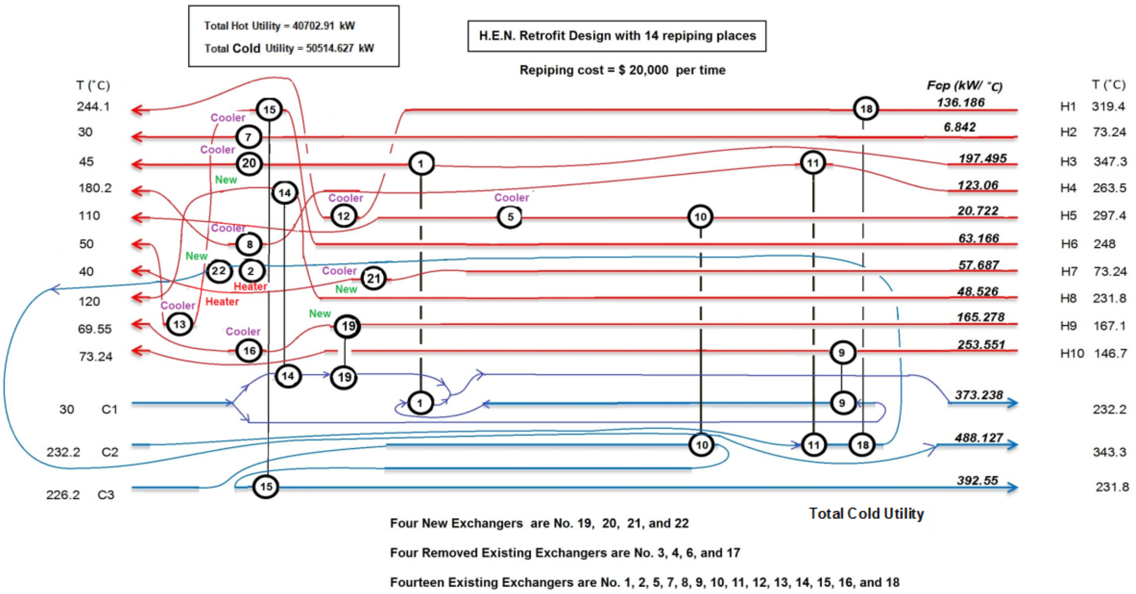

Figure 5: The Grid diagram of retrofit case from our work with repiping representation

Exchangers in the retrofitted network are summarized in Table 3. Set The total retrofitted area of process exchanger is 6,455.15 m^2. As the result of increased heat recovery, the usages of hot and cold utilities are decreased to 40,702.91 kW and 50,514.627 kW. The heat recovery improvement in the retrofitted network results in positive NPV: the hot and cold utilities usage are reduced by 40 % and 33 %, the energy savings is over 3.87 M$/y, the NPV is 11,772,466 $. For the modification on the retrofit case, one splitting is introduced to the cold stream J1 and four new exchangers are used in our retrofitted HEN.

Table 2: The film coefficient stream

Stream	*h*, film coefficient (kW/m^2/°C)		Stream	*h*, film coefficient (kW/m^2/°C)	
H1	1.293		H10	0.502	(126.7 < T < 146.7)
H2	5.063			0.937	(99.94 < T < 126.7)
H3	0.892	(202.7 < T < 347.3)		1.912	(73.24 < T < 99.94)
	0.633	(45 < T < 202.7)	HU1	6	for HX No. 9 and 17
H4	1.361		HU2	0.1112	for HX No. 18
H5	1.299	(203.2 < T < 297.4)	C1	0.5165	(30 < T < 108.1)
	1.099	(110 < T < 203.2)		0.655	(108.1 < T < 211.3)
H6	1.344	(147.3 < T < 248)		0.615	(211.3 < T < 232.2)
	1.056	(50 < T < 147.3)	C2	0.788	
H7	1.28		C3	3.328	(226.2 < T < 228.7)
H8	1.396	(176 < T < 231.8)		3.079	(228.7 < T < 231.8)
	1.347	(120 < T < 176)	CU1	3.753	for HX No. 7, 4, 8, 2, 3, 13, and 16
H9	1.388	(116.1 < T < 167.1)	CU2	6	for HX No. 14
	1.357	(69.55 < T < 116.1)	CU3	6	for HX No. 15

6. Conclusions

In this work, a retrofit model based on the stagewise superstructure, as proposed by (Yee and Grossmann, 1991) is proposed. This model includes use of the existing area and the buying of new area. The stream splitting is allowed to increase the possibility of potential match, resulting in utility cost reduction. The systematic approach is applied to utilize the existing exchangers to save cost of new exchanger for HEN retrofit. A case study, this work provides HEN retrofit design, having lower investment costs, more practical and simple structure than the optimum network reported in the literature. The previous work introduced many splitting and used less existing exchangers than our work.

Table 3: Heat exchangers from HEN retrofit results

HX No.	$Match^{New}$ ($Match^{Exist}$)	A^{new} (A^{Exist})	HX No.	$Match^{New}$ ($Match^{Exist}$)	A^{new} (A^{Exist})
1	I3J1 (I3J1)	2,749.32 (3,280)	12	I1CU1 (I5J1)	35.10 (36)
2	J2HU2 (I7CU1)	53.22 (62.6)	13	I6CU1 (I9CU1)	150.07 (182.57)
3	*No match* (I8CU1)	0 (33.6)	14	I8J1 (I4CU2)	1023..68(101.27)
4	*No match* (I5CU1)	0 (4.08)	15	I6J3 (I1CU3)	98.20 (93.8)
5	I5CU1 (I5J1)	26.38 (27.4)	16	I9CU1 (I10CU1)	175.14 (250.9)
6	*No match* (I8J1)	0 (21.2)	17	*No match* (J3HU1)	0 (51.7)
7	I2CU1 (I2CU1)	6.04 (5.63)	18	I1J2 (J2HU)	944.87 (942)
8	I4CU1 (I6CU1)	129.64 (153)	19 (New)	I9J1	666.40
9	I10J1 (J1HU)	112.24 (1,071)	20 (New)	I3CU1	520.64
10	I5J3 (I5J2)	63.86 (67.6)	21 (New)	I7CU1	86.56
11	I4J2 (I3J2)	746.57 (688)	22 (New)	J2HU1	4000

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