CHAPTER IV
RESULTS AND DISCUSSION

4.1 Retrofit Case Study

4.1.1 Introduction

This problem considers the retrofit of a heat exchanger network of a crude distillation unit with pre-flash drum, as shown in Figure 4.1, with 11 streams and 9 exchangers, the base case of CDU is operated under TROLL (light crude), FOROZAN (medium crude) and SOUEDIE (heavy crude), (http://www.bp.com) with different distillation curves (Figure 4.2). The properties of the light crude, medium crude and heavy crude are shown in Tables 4.2-4.5. Crude is preheated to a temperature of 125 °C, for desalting purposes. After that crude is preheated to 170 °C in order to preflash before is heated to 370 °C and then enter to the distillation column. In this example, 5 - 95 gaps and ASTM D86 (95 % point) of product are used as separation criteria. The term gap refers to the difference between the 5% ASTM D86 distillation temperature of a heavier product and the 95 % ASTM D86 distillation temperature of an adjacent lighter product. When the distillation curves of the two products overlap, a negative gap appears. Table 4.6 indicates the specifications of the products and the product withdraw locations. The column data are shown in Table 4.7. Table 4.8 shows the set of design variables.

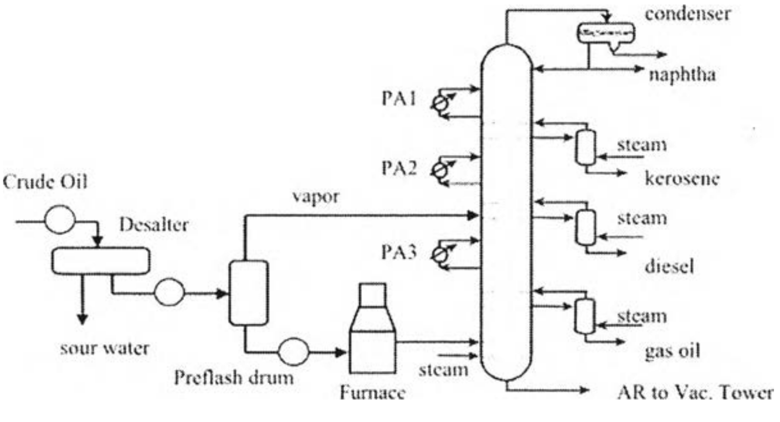

Figure 4.1 The crude distillation unit with pre-flash drum.

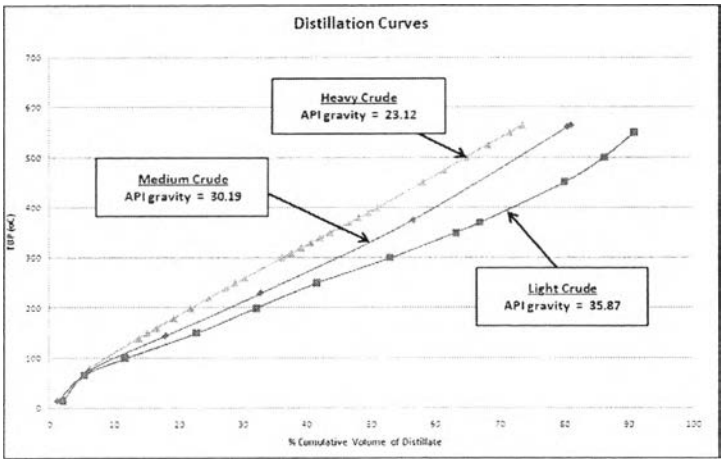

Figure 4.2 Distillation curves of multiple crude.

Table 4.1 Crude used for study case

Crude	API	Throughput (m^3/hr)
Light crude	35.87	795
Medium crude	30.19	795
Heavy crude	23.12	795

Table 4.2 TBP data of Light crude

Vol %	Temperature (°C)
2.2	15
5.6	65
11.9	100
22.8	150
32.3	200
41.8	250
53.2	300
63.5	350
67.2	370
80.2	450
86.5	500
91.0	550

Table 4.3 TBP data of Medium crude

Vol %	**Temperature (°C)**
1.3	15
6.3	75
18.0	145
33.0	230
56.8	375
80.6	560
81.2	565

Table 4.4 TBP data of Heavy crude

Vol %	**Temperature (°C)**	**Vol %**	**Temperature (°C)**
13.9	140	43.9	350
15.3	150	45.4	360
16.7	160	46.9	370
19.4	180	48.3	380
22.0	200	49.8	390
24.7	220	51.2	400
27.5	240	58.3	450
29.0	250	61.7	475
30.4	260	65.1	500
36.3	300	68.4	525
37.8	310	71.7	550
39.4	320	73.7	565
40.9	330		

Table 4.5 Light-end composition of crude

Compound	**Vol %**		
	Light crude	**Medium crude**	**Heavy crude**
Ethane	0.22	0.01	0
Propane	0.58	0.28	0.07
i-Butane	0.39	0.26	0.13
n-Butane	1.04	0.97	0.63

Table 4.6 Specifications of the products

Product	Specification	Withdrawal tray
Naphtha	D86 (95 % point) = 182 °C	1
Kerosene	D86 (95 % point) = 271 °C	9
Diesel	D86 (95 % point) = 327 °C	17
AGO	D86 (95 % point) = 410 °C	28
Overflash rate	0.01	
Kerosene-Naphtha	(5-95) Gap = 17.2 °C	
Diesel-Kerosene	(5-95) Gap = 0.6 °C	
AGO-Diesel	(5-95) Gap = -3.4 °C	
Feed tray		29
Total trays		34

Table 4.7 Column data

Number of Plates	34
Number of trays (Side Strippers)	4
Pump-around 1 (PA1) Draw	Tray 4
Pump-around 1 (PA1) Return	Tray 2
Pump-around 2 (PA2) Draw	Tray 12
Pump-around 2 (PA2) Return	Tray 10
Pump-around 3 (PA3) Draw	Tray 21
Pump-around 3 (PA3) Return	Tray 19
Kerosene Side-Stripper Return	Tray 8
Diesel Side-Stripper Return	Tray 16
AGO Side-Stripper Return	Tray 26
Crude Feed	Tray 29

Table 4.8 Design variables

Variable	Value		
	Light crude	Medium crude	Heavy crude
Kerosene Stripper Steam @ 260 °C, 4.4 atm (kg/hr)	522.5	832.5	818.6
Diesel Stripper Steam @ 260 °C, 4.4 atm (kg/hr)	2616.5	2080.6	2217.5
AGO Stripper Steam @ 260 °C, 4.4 atm (kg/hr)	2843.0	1860.0	1696.0
Main Steam @ 260 °C, 4.4 atm (kg/hr)	3493		
Overflash	1 %		
Condensor Temperature	32.22 °C		
Pump-around 1 (PA1) Return Temperature	104.44 °C		
Pump-around 2 (PA2) Return Temperature	148.89 °C		
Pump-around 3 (PA3) Return Temperature	232.22 °C		
Pump-around 1 (PA1) Heat Rate	11.7 MW		
Pump-around 2 (PA2) Heat Rate	8.8 MW		
Pump-around 3 (PA3) Heat Rate	8.8 MW		

The existing exchanger network configuration is shown in Figure 4.3. The existing network does not have splitters. The stream properties are shown in Table 4.9, 4.10 and 4.11, the existing heat exchangers areas and heat load are shown in Table 4.12. The original HEN consumes 315539 MW/hr of hot utility and 149255 MW/hr of cold utility. The results will be compared for a project life of 5 years, 10 % interest rate and presented in the discussion section. 350 working days per year is assumed. The costs of hot and cold utilities are 0.4431 and 0.0222 cent/MJ, respectively.

The maximum values of area addition and reduction that can be made to existing shells are 20 % and 50 % of the corresponding existing area; respectively. The maximum area per shell is 5,000 (m^2), the maximum number of shells per exchanger is 4. The model was run for maximizing the net present value (NPV). The cost relations for area adjustment are shown Equation 4.1, 4.2, 4.3 and 4.4. Costs are assigned to splitting of 20,000 \$ and to relocation of 25,000 \$.

$$\text{Exchanger (\$)} = 8{,}600 + [670\times \text{Area}^{0.83}\,(\text{m}^2)] \tag{4.1}$$

$$\text{Area addition (\$)} = 4{,}300 + [1476\times \text{ Added Area}^{0.83}\,(\text{m}^2)] \tag{4.2}$$

$$\text{Area reduction (\$)} = 4{,}300 + [9\times \text{ Reduced Area}^{0.83}\,(\text{m}^2)] \tag{4.3}$$

$$\text{New shell (\$)} = 8{,}600 + [1476\times \text{Area of shell}^{\,0.83}(\text{m}^2)] \tag{4.4}$$

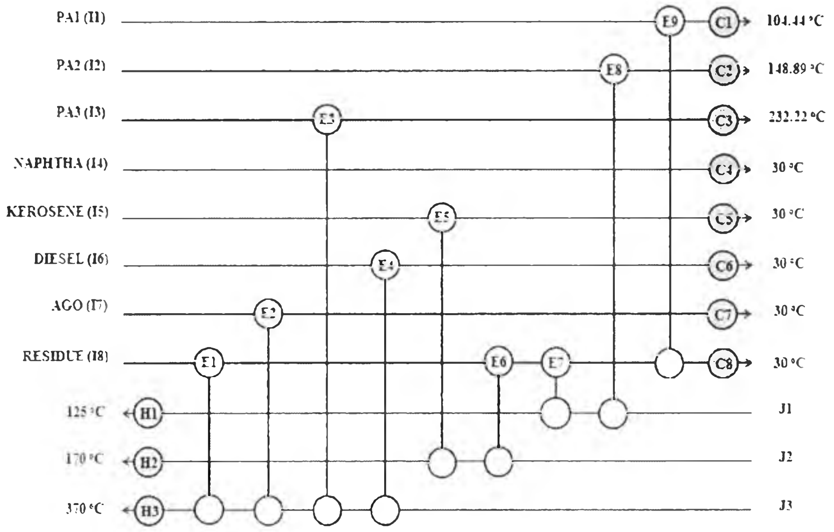

Figure 4.3 Existing heat exchanger network.

Table 4.9 Stream properties of Light crude

Stream	FCp (kW/ °C)	T_{in} (°C)	T_{out} (°C)	h (kW/m^2 °C)	H (kW)
I1	121.02	201.17	104.44	1.293	11707
I2	69.91	274.71	148.89	1.318	8796
I3	98.60	321.17	232.22	1.298	8771
I4	105.22	32.22	30	1.058	234
I5	67.76	234.40	30	1.395	13850
I6	49.64	273.17	30	1.423	12072
I7	59.98	326.40	30	1.343	17779
I8	135.33	341.73	30	0.892	42186
J1	380.57	25	125	0.654	38057
J2	434.32	125	170	0.632	19544
J3	585.63	166.64	370	0.788	119092

Table 4.10 Stream properties of Medium crude

Stream	FCp (kW/ °C)	T_{in} (°C)	T_{out} (°C)	h (kW/m^2°C)	H (kW)
I1	125.28	198.28	104.44	1.092	11756
I2	71.80	271.63	148.89	1.235	8812
I3	101.36	319.12	232.22	1.270	8808
I4	92.01	32.22	30	1.253	204
I5	56.28	225.57	30	1.394	11007
I6	34.77	269.78	30	1.431	8338
I7	41.91	326.26	30	1.413	12415
I8	210.12	357.39	30	0.888	68791
J1	387.57	25	125	0.652	38757
J2	443.70	125	170	0.630	19967
J3	587.80	168.84	370	0.782	118241

Table 4.11 Stream properties of Heavy crude

Stream	FCp (kW/ °C)	T_{in} (°C)	T_{out} (°C)	h (kW/m^2 °C)	H (kW)
I1	132.07	193.31	104.44	1.075	11737
I2	74.03	267.77	148.89	1.221	8801
I3	104.43	316.69	232.22	1.270	8821
I4	70.64	32.22	30	1.309	157
I5	46.81	221.36	30	1.393	8957
I6	29.33	263.57	30	1.438	6851
I7	32.46	322.00	30	1.419	9478
I8	268.65	353.52	30	0.826	86914
J1	392.24	25	125	0.651	39224
J2	449.76	125	170	0.630	20239
J3	555.77	167.81	370	0.780	112370

Table 4.12 The existing heat exchangers areas and heat load

Exchanger	Area (m^2)	Heat Load (kW)		
		Light crude	Medium crude	Heavy crude
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

4.1.2 Discussion

In this section the results for each retrofitted designs are compared to find the optimum retrofitted design which gives the maximum NPV. Each retrofitted design was performed using the specified constraints and cost functions. The relocation concept was used to manipulate the area of existing exchangers as well as adding new exchangers and introducing split streams.

4.4.2.1 Retrofit Potential and Design Results

From process pinch analysis by the retrofit potential program the maximum NPV of retrofitted Light crude, Medium crude and Heavy crude design occur at ΔT_{min} of 34.65 °C, 29.80 °C and 55.0 °C respectively. The composite curves of the optimum retrofitted Light crude, Medium crude and Heavy crude are shown in Figure 4.4, 4.6 and 4.8 respectively. The NPV diagrams of the optimum retrofitted Light crude, Medium crude and Heavy crude are shown in Figure 4.5, 4.7 and 4.9 respectively.

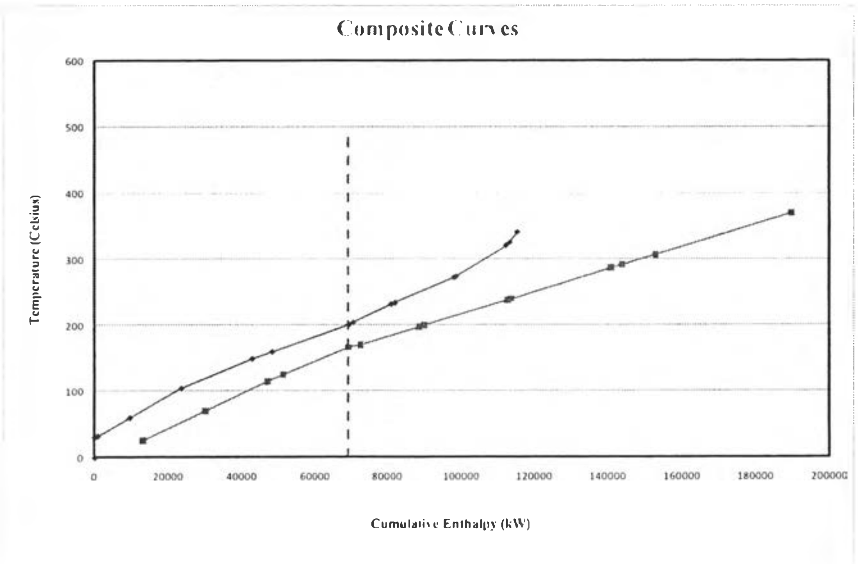

Figure 4.4 Composite curves of the optimum retrofitted Light crude.

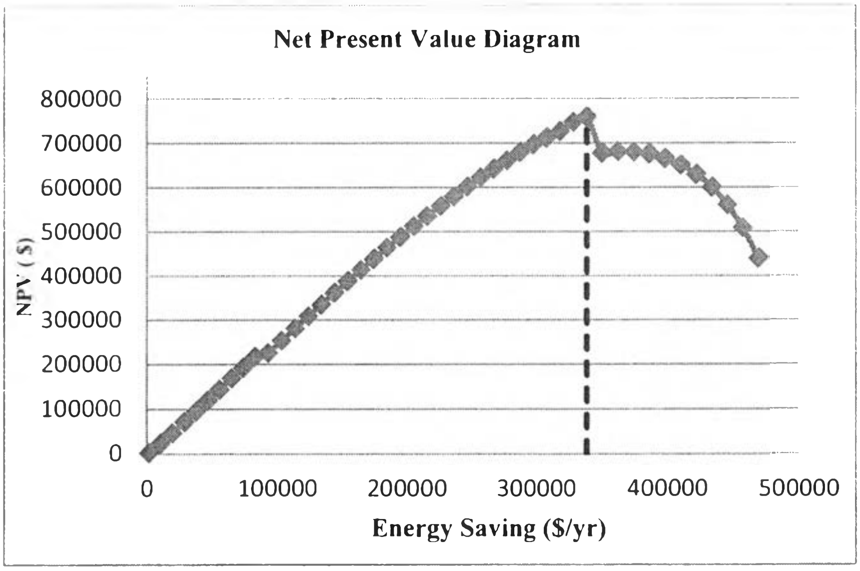

Figure 4.5 NPV diagrams of the optimum retrofitted Light crude.

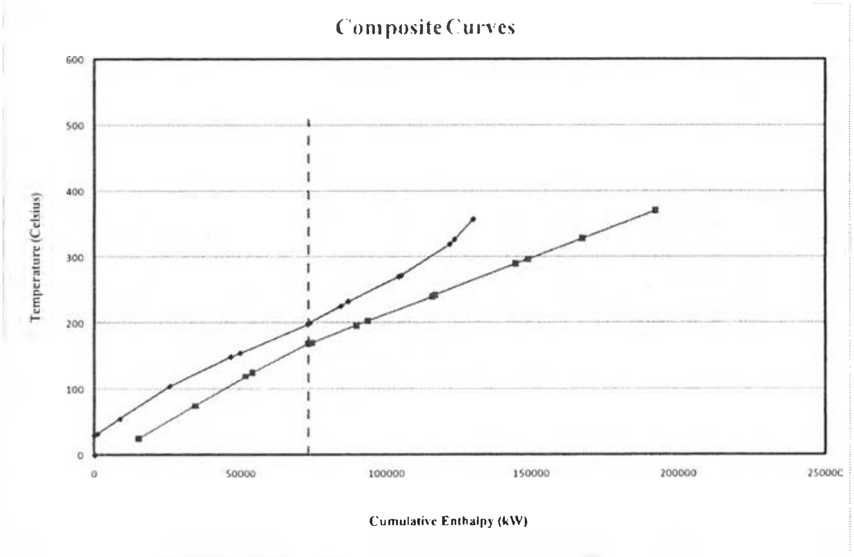

Figure 4.6 Composite curves of the optimum retrofitted Medium crude.

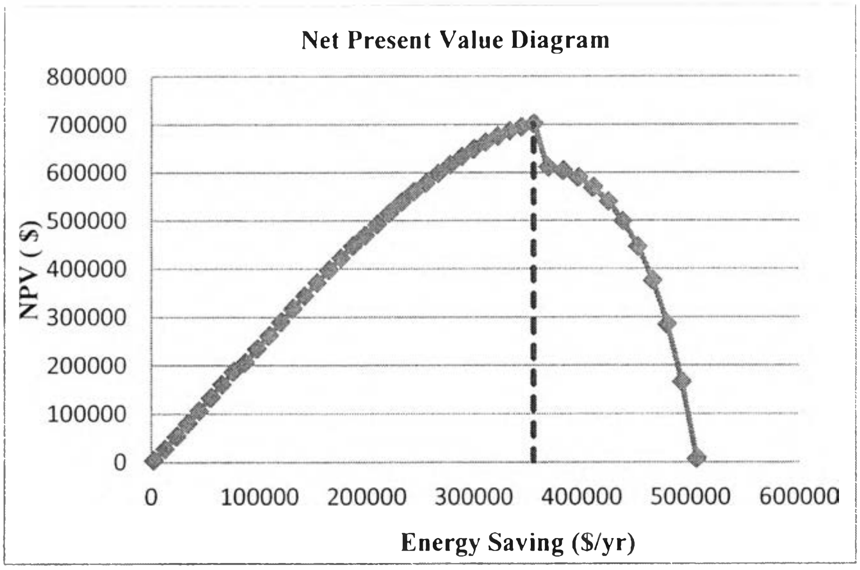

Figure 4.7 NPV diagrams of the optimum retrofitted Medium crude.

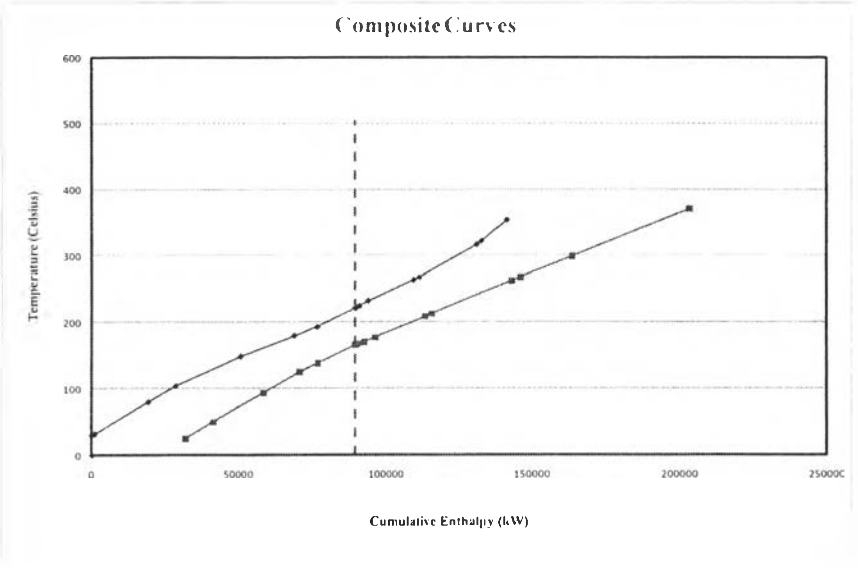

Figure 4.8 Composite curves of the optimum retrofitted Heavy crude

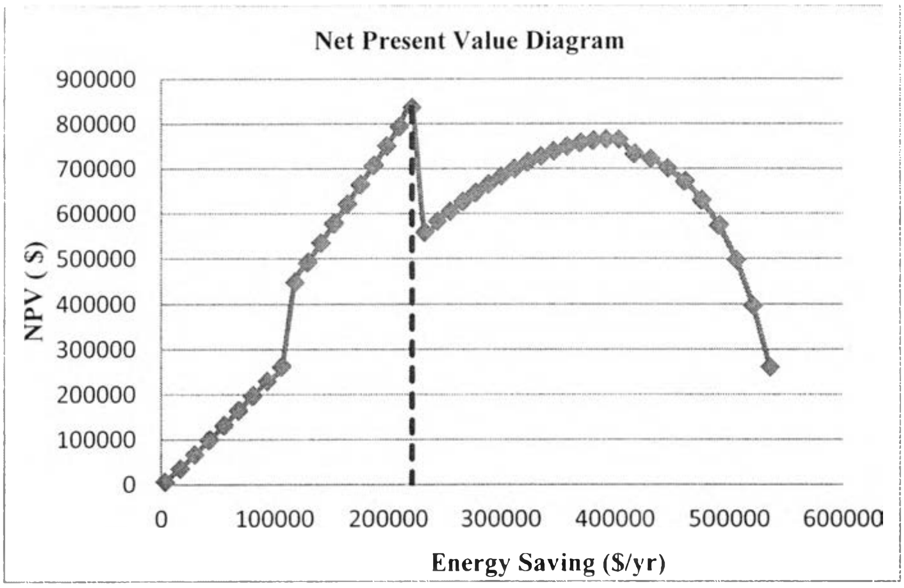

Figure 4.9 NPV diagrams of the optimum retrofitted Heavy crude.

Now that the optimum ΔT_{min} value has been defined, Table 4.13 shows the optimum ΔT_{min} and the pinch temperature of each retrofit case. The next step is to generate the stream matches for heat exchange in the new network. To do this, a grid diagram of the process is analyzed with the pinch temperature represented as two vertical lines at the middle of the grid. The grid diagram for the retrofitted network of HEN of Light crude, Medium crude and Heavy crude are illustrated in Figure 4.10, 4.11 and 4.12.

Table 4.13 The optimum ΔT_{min} and the pinch temperature of each retrofit case

	Light Crude	Medium Crude	Heavy Crude
Optimum ΔT_{min}(°C)	34.65	29.80	55.00
Pinch temperature of hot stream(°C)	198.28	201.17	221.36
Pinch temperature of cold stream(°C)	168.48	166.53	166.36

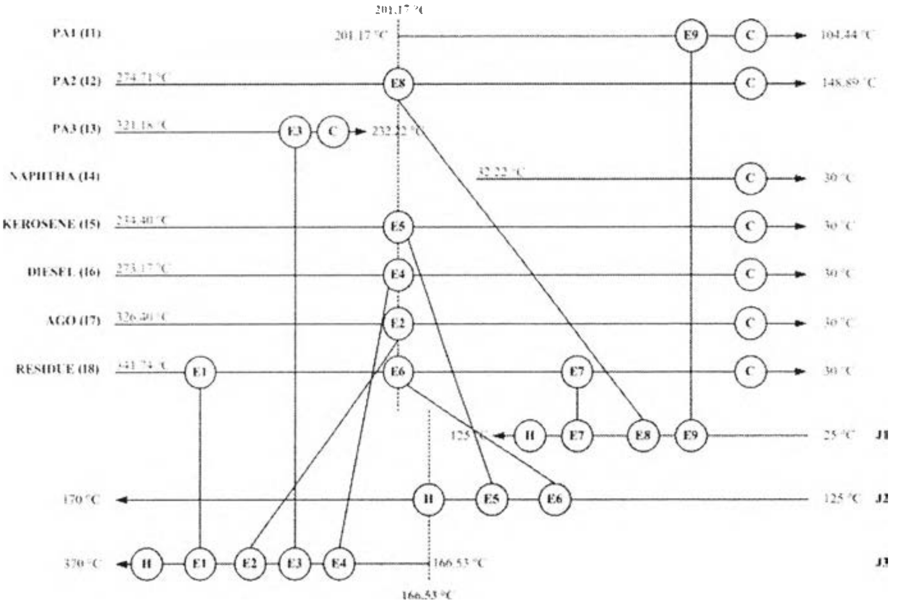

Figure 4.10 Grid diagram for the retrofitted network of HEN of Light crude.

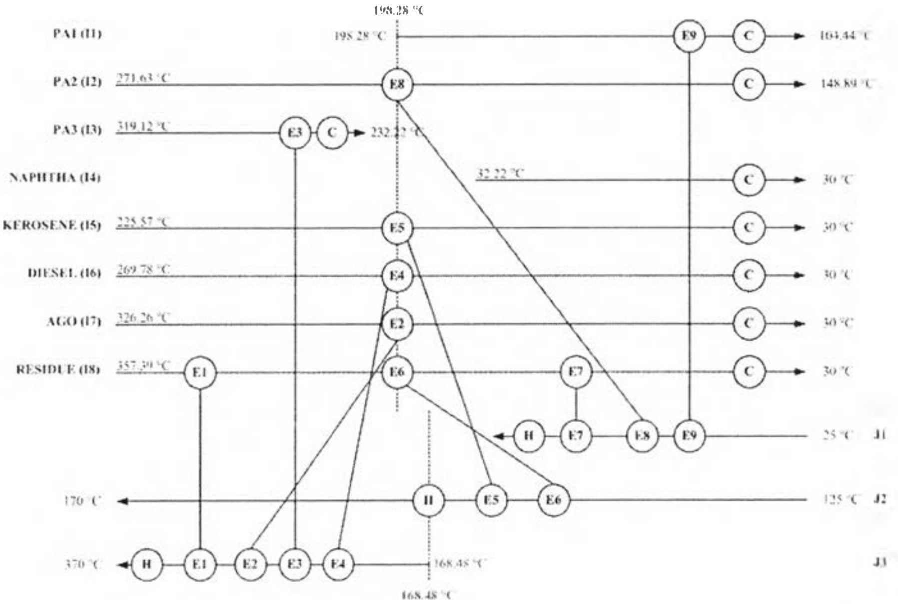

Figure 4.11 Grid diagram for the retrofitted network of HEN of Medium crude.

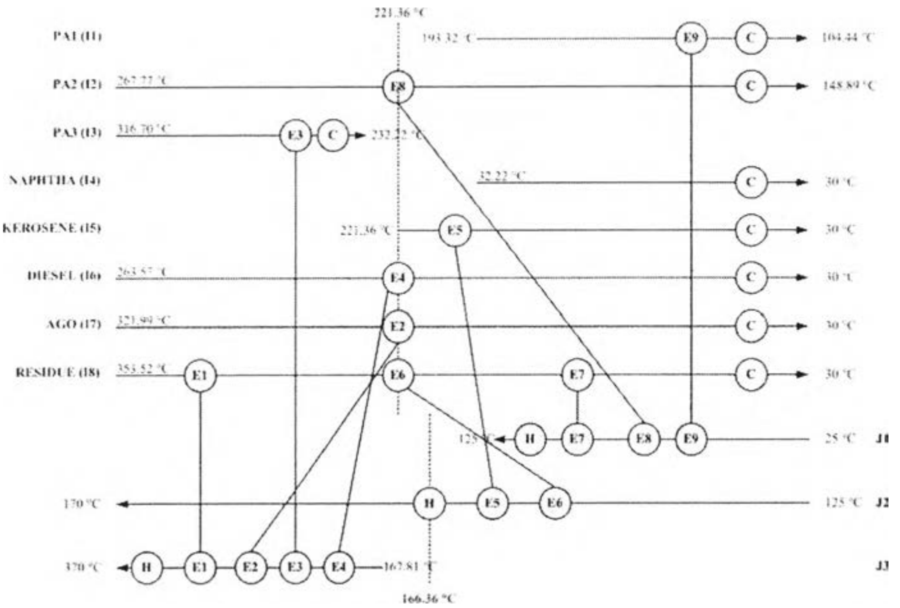

Figure 4.12 Grid diagram for the retrofitted network of HEN of Heavy crude.

The first step to design the new network is to locate the existing exchangers that transfer heat across the pinch. Because pinch technology does not allow cross-pinch heat transfer, these exchangers must be eliminated and essentially reused. It can be done by moving each exchanger to one side of the pinch and then altering the input and target temperatures to ensure that no cross-pinch heat transfer occurs in the new design. As a reminder, the sections above and below the pinch must be analyzed separately.

Then the stream matches are generated by using a mixed integer linear programming (MILP) model using GAMS called the stage model, from Yee and Grossmann (1990). The objective function is to minimize the number of exchanger under constraint functions of energy balance, thermodynamics and logical constraint. At the pinch, use value of EMAT equal to ΔT_{min} from pinch analysis. As matches move away from the pinch, use value of EMAT equal to 5 °C. The retrofitted design of Light crude base, Medium crude base and Heavy crude base are shown in Figure 4.13, 4.14 and 4.15, respectively.

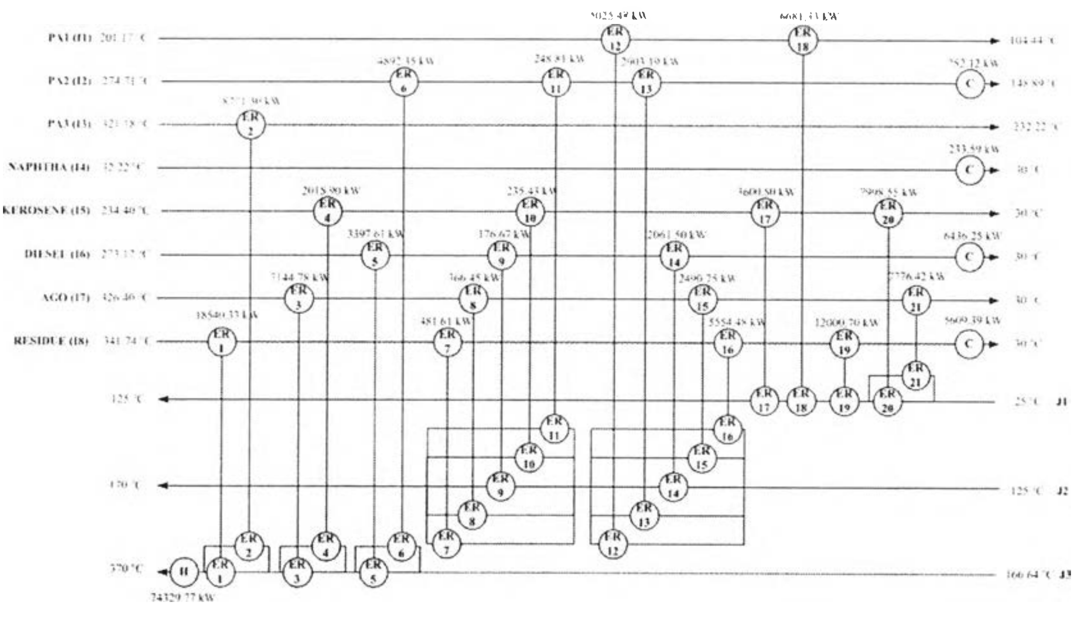

Figure 4.13 Retrofitted design of Light crude base.

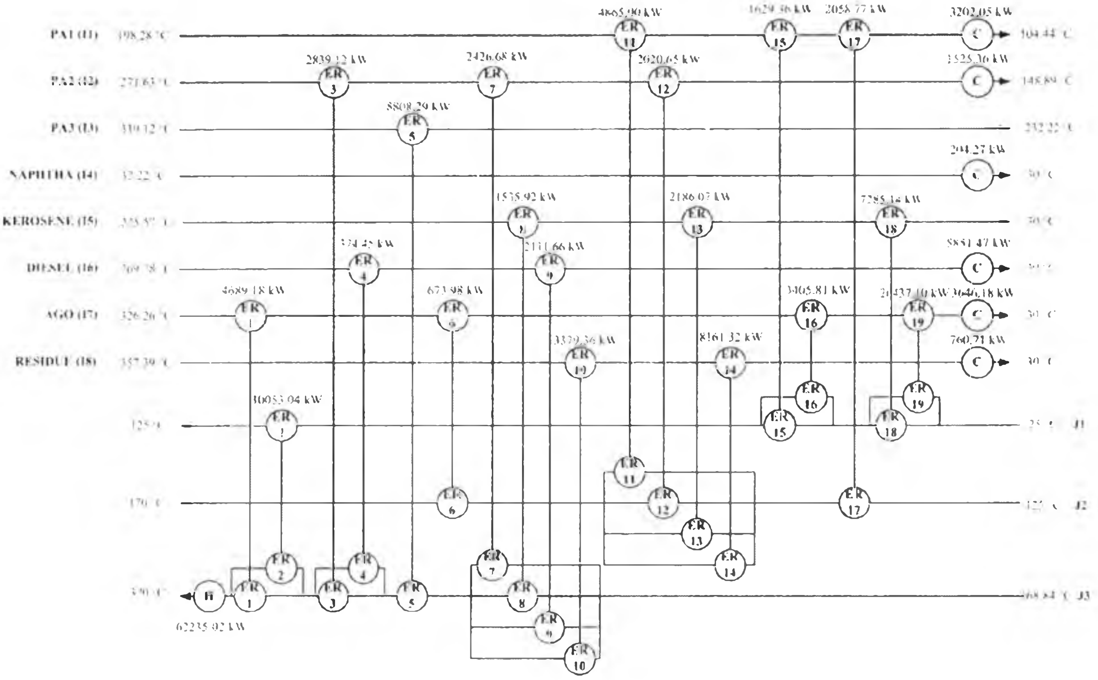

Figure 4.14 Retrofitted design of Medium crude base.

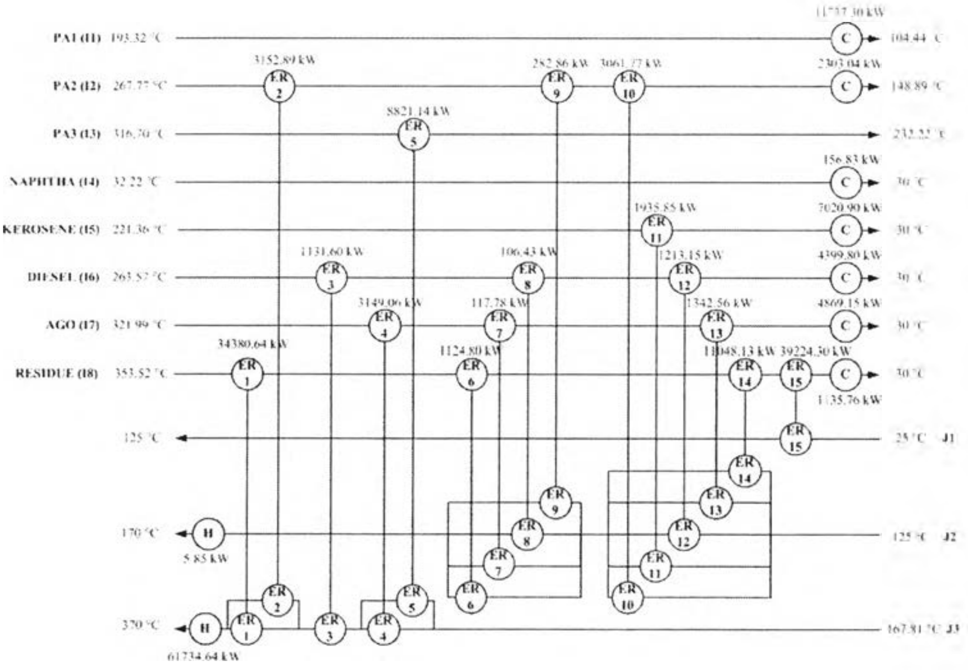

Figure 4.15 Retrofitted design of Heavy crude base.

4.4.2.2 Simulation Retrofit Design Results

Then PROII is simulated to perform the utility consumption of multiple crudes (Table 4.17) with the HEN retrofit design from previous step. The duties and the overall heat transfer coefficient of each exchanger are defined. Then PROII will calculate area of each exchanger. Furthermore PROII is also used to validate the retrofit design. Table 4.14, 4.15 and 4.16 show the area of each exchanger from PROII simulation

Table 4.14 Exchangers areas of Light crude from PROII simulation

Exchanger	Area (m^2)	Exchanger	Area (m^2)
ER1	1169.35	ER12	333.36
ER2	465.76	ER13	186.04
ER3	208.13	ER14	138.16
ER4	166.18	ER15	113.19
ER5	137.73	ER16	281.61
ER6	160.22	ER17	139.54
ER7	24.79	ER18	867.83
ER8	16.53	ER19	855.32
ER9	12.24	ER20	623.12
ER10	13.99	ER21	832.65
ER11	15.51		

Table 4.15 Exchangers areas of Medium crude from PROII simulation

Exchanger	Area (m^2)	Exchanger	Area (m^2)
ER1	348.64	ER11	398.58
ER2	1773.35	ER12	130.83
ER3	149.86	ER13	144.67
ER4	13.80	ER14	442.82
ER5	254.70	ER15	111.95
ER6	29.60	ER16	165.43
ER7	132.65	ER17	451.50
ER8	89.01	ER18	804.57
ER9	78.60	ER19	2355.63
ER10	174.03		

Table 4.16 Exchangers areas of Heavy crude from PROII simulation

Exchanger	Area (m^2)	Exchanger	Area (m^2)
ER1	1377.43	ER9	11.85
ER2	518.49	ER10	128.83
ER3	44.61	ER11	77.63
ER4	64.78	ER12	44.10
ER5	201.95	ER13	43.84
ER6	42.86	ER14	415.66
ER7	3.93	ER15	3220.47
ER8	4.01		

Table 4.17 Utility consumption of retrofit designs

	Light crude	Medium crude	Heavy crude
Hot utility (MJ/hr)	241069	234224	302620
Cold utility (MJ/hr)	39666	68022	136418

4.2.2.3 Relocation Results

After retrofit and simulation step is complete, HEN structure changes using the existing exchangers in retrofit network is not specified. It shows where the base case exchanger are used or relocated in the retrofit case, resulting in the optimal HEN with the retrofit structure. Relocation concept is to relocate the base-case exchangers to the new location of the retrofit, with small area added or removed.

Table 4.18 Retrofitted heat exchanger results of Light crude

Number of exchangers	Matching	Add (+) or Remove (-) areas to existing/new exchangers	Area(m^2)	% Add/ Remove	Note
ER1	I8-J3	E1-48.65	1169.35	-3.99	**Relocation/Remove area**
ER2	I3-J3	E6-18.24	465.76	-3.77	**Relocation/Remove area**
ER3	I7-J3	-	208.13	-	**New Exchanger**
ER4	I5-J3	E9-15.82	166.18	-8.69	**Relocation/Remove area**
ER5	I6-J3	-	137.73	-	**New Exchanger**
ER6	I2-J3	-	160.22	-	**New Exchanger**
ER7	I8-J2	-	24.79	-	**New Exchanger**
ER8	I7-J2	-	16.53	-	**New Exchanger**
ER9	I6-J2	-	12.24	-	**New Exchanger**
ER10	I5-J2	-	13.99	-	**New Exchanger**
ER11	I2-J2	-	15.51	-	**New Exchanger**
ER12	I1-J2	E4-101.64	333.36	-23.37	**Relocation/Remove area**
ER13	I2-J2	-	186.04	-	**New Exchanger**
ER14	I6-J2	-	138.16	-	**New Exchanger**
ER15	I7-J2	E3+38.19	113.19	50.92	**Relocation/New Shell**
ER16	I8-J2	E7-179.39	281.61	-38.91	**Relocation/Remove area**
ER17	I5-J1	E8-2.46	139.54	-1.74	**Relocation/Remove area**
ER18	I1-J1	E2-167.17	867.83	-16.15	**Relocation/Remove area**
ER19	I8-J1	-	855.32	-	**New Exchanger**
ER20	I5-J1	E5+138.12	623.12	28.48	**Relocation/New Shell**
ER21	I7-J1	-	832.65	-	**New Exchanger**

Table 4.19 Retrofitted heat exchanger results of Medium crude

Number of exchangers	Matching	Add (+) or Remove (-) areas to existing/new exchangers	Area(m^2)	% Add/ Remove	Note
ER1	I7-J3	E5-136.36	348.64	-28.12	**Relocation/Remove area**
ER2	I8-J3	E1+555.35	1773.35	45.60	**Relocation/New Shell**
ER3	I2-J3	-	149.86	-	**New Exchanger**
ER4	I6-J3	-	13.80	-	**New Exchanger**
ER5	I3-J3	-	254.70	-	**New Exchanger**
ER6	I7-J2	-	29.60	-	**New Exchanger**
ER7	I2-J3	E8-9.35	132.65	-6.58	**Relocation/Remove area**
ER8	I5-J3	-	89.01	-	**New Exchanger**
ER9	I6-J3	E3+3.60	78.60	4.81	**Relocation/Add area**
ER10	I8-J3	E9-7.97	174.03	-4.38	**Relocation/Remove area**
ER11	I1-J2	E4-36.42	398.58	-8.37	**Relocation/Remove area**
ER12	I2-J2	-	130.83	-	**New Exchanger**
ER13	I5-J2	-	144.67	-	**New Exchanger**
ER14	I8-J2	E6-41.18	442.82	-8.51	**Relocation/Remove area**
ER15	I1-J1	-	111.95	-	**New Exchanger**
ER16	I7-J1	-	165.43	-	**New Exchanger**
ER17	I1-J2	E7-9.50	451.50	-2.06	**Relocation/Remove area**
ER18	I5-J1	E2-230.43	804.57	-22.26	**Relocation/Remove area**
ER19	I8-J1	-	2355.63	-	**New Exchanger**

Table 4.20 Retrofitted heat exchanger results of Heavy crude

Number of exchangers	Matching	Add (+) or Remove (-) areas to existing/new exchangers	Area(m^2)	% Add/ Remove	Note
ER1	I8-J3	E1+159.43	1377.43	13.09	**Relocation/Add area**
ER2	I2-J3	E2-516.51	518.49	-49.90	**Relocation/Remove area**
ER3	I6-J3	-	44.61	-	**New Exchanger**
ER4	I7-J3	E3-10.22	64.78	-13.62	**Relocation/Remove area**
ER5	I3-J3	E9+19.95	201.95	10.96	**Relocation/Add area**
ER6	I8-J2	-	42.86	-	**New Exchanger**
ER7	I7-J2	-	3.93	-	**New Exchanger**
ER8	I6-J2	-	4.01	-	**New Exchanger**
ER9	I2-J2	-	11.85	-	**New Exchanger**
ER10	I2-J2	E8-13.17	128.83	-9.27	**Relocation/Remove area**
ER11	I5-J2	-	77.63	-	**New Exchanger**
ER12	I6-J2	-	44.10	-	**New Exchanger**
ER13	I7-J2	-	43.84	-	**New Exchanger**
ER14	I8-J2	E4-19.34	415.66	-4.45	**Relocation/Remove area**
ER15	I8-J1	E5+2735.47	3220.47	564.01	**Relocation/New Shell**

4.2.2.4 Cost Evaluation Results

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 given by Equation 4.5:

$$\mathrm{NPV} = \sum_{t=1}^{n\ \mathrm{years}} \left(\frac{\mathrm{Utility\,saving\,cost}_i}{(1 + \mathrm{Annual\,interest\,rate})^i} \right) - \mathrm{Total\,investment\,cost} \qquad (4.5)$$

Table 4.21 Cost summary

	Retrofit Design		
	Light crude	**Medium crude**	**Heavy crude**
no.of new exchanger	12	10	8
Area of new exchanger	2601.31	3445.49	272.83
no. of used existing exchanger	9	9	7
Added Area	0	3.6	179.38
Removed area	533.37	471.21	559.24
no.of new shell	2	1	1
Area of new shell	176.31	555.35	2735.47
Investment cost for 5 years life time ($)	771.578	1.042,097	1,385,774
Annualize investment cost ($/yr)	154,316	208,419	277.155
Heating Utility (MJ/yr)	2,024,982.526	1,967,478,709	2,542,007,559
Cooling Utility (MJ/yr)	333,194,353	571,382,662	1,145,910,849
Energy saving ($/yr)	2.976.183	3.178.105	504,822
Splitting cost ($)	20,000	20.000	20,000
Relocation cost ($)	25.000	25,000	25,000
NPV ($)	10,510,498	11,005,420	527,899
Total Utility consumption (MJ/yr)	2,358,176,905	2,538,861,370	3,687,918,407

The Table 4.21 represents the cost summary. It is clear that the retrofitted design of Medium crude base has the highest NPV of.11,005,420 $ for a 5-years lifetime and resulting in total utility saving of 35 %.Thereforethe retrofitted design of Medium crude base is the optimal retrofit design processing three types of crude.