CHAPTER IV

RESULTS AND DISCUSSION

This research focuses on the performance of constraint function of retrofit with/without relocation. The existing heat exchanger network (HEN) is generated for testing by using MILP mode with GAMS software which is applied for retrofit without relocation and retrofit with relocation. Existing HEN for the test case consists of three hot streams (I1, I2, I3) and three cold streams (J1, J2, J3) .There are two hot process streams (I1, I2) with one hot utility stream (I3) and two cold process steams(J1,J2) with one cold utility stream (J3).Their supplied and target temperatures and the heat capacity (Fcp) are shown in Figure 4.1

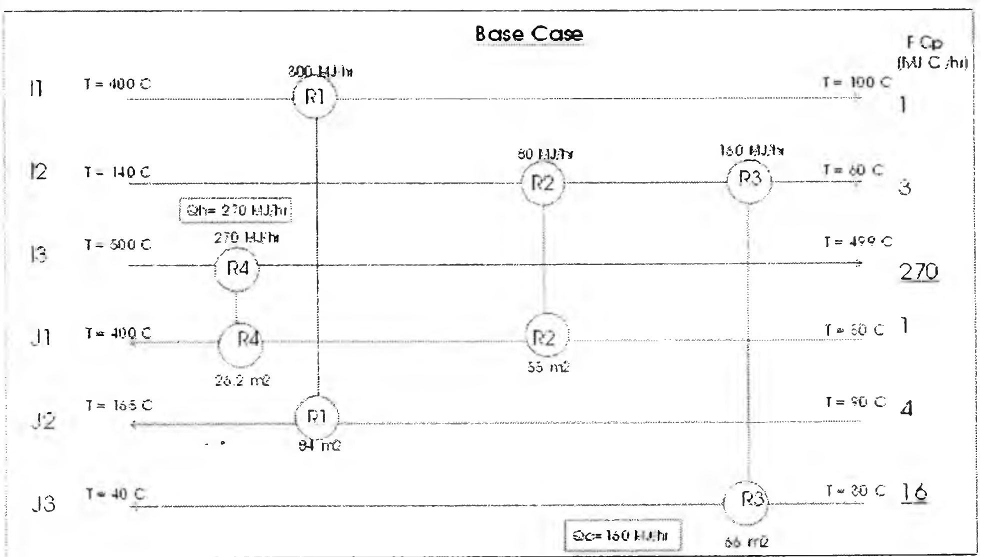

Figure 4.1 Existing heat exchanger network (BASE CASE)
Qh = 270 MJ/hr, Qc = 160 MJ/hr

The existing HEN consists of four heat exchangers (Hex), first exchanger is R1 (I1, J2) with existing area=84 m^2 and heat transferring =300 MJ/hr. Second exchanger is R2 (I2, J1) with existing area =55 m^2 and heat transferring 80 MJ/hr. Third exchanger is R3 (I2, J3) with existing area=66 m^2 and heat transferring160 MJ/hr. Fourth exchanger is R4 (I3, J1) which has existing area=26.2 m^2 and heat transferring 270MJ/hr. Stream properties of existing HEN are shown in Table 4.1 and properties of existing exchanger is shown in Table 4.2 Cost data and total cost of existing are shown in Table 4.3 and 4.4.

Table 4.1 Properties of stream of existing HEN

Stream	F (Ton/hr)	Cp (kJ/kg-°C)	h (MJ/h-m²-°C)	Tin (°C)	Tout (°C)
I1	1	1	0.1	400	100
I2	3	1	0.1	140	60
I3	270	1	0.1	500	499
J1	1	1	0.1	50	400
J2	4	1	0.1	90	165
J3	16	1	0.1	30	40

Table 4.2 Properties of all heat exchangers in existing HEN

HEX	Q (MJ/hr)	Existing area (m²)
R1	300	84
R2	80	55
R3	160	66
R4	270	26.2

Table 4.3 Cost data for existing HEN

Utilities	Cost $/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost 1000+20 A $/yr	

Table 4.4 Total cost of existing HEN

Case	Hot utility (MJ/hr)	Cold utility (MJ/hr)	Operating Cost ($/yr)	Total cost ($/yr)
Existing HEN	270	160	28860.8	28860.8

4.1 Retrofit without relocation

4.1.1 Study Relationship between Investment Cost (fixed & area cost) and Energy Consumption in Retrofit HEN.

4.1.1.1 Retrofit without relocation when Fixed cost=1$/yr and Area cost =1 $/yr

Relationship between investment cost (Fixed & area cost) and energy consumption is studied. When fixed cost =1 $/yr and area cost =1 $/yr with condition (BIF=0) only one exchanger is allowed for the same hot-cold-stream matching and every stream can be split. And cost data for this case is shown in Table 4.5. The existing HEN is shown in Figure 4.1. The retrofit network is show in Figure 4.2.

Table 4.5 Cost data for case study 4.1.1.1

Utilities	Cost \$/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost(1)+(1) A \$/yr	

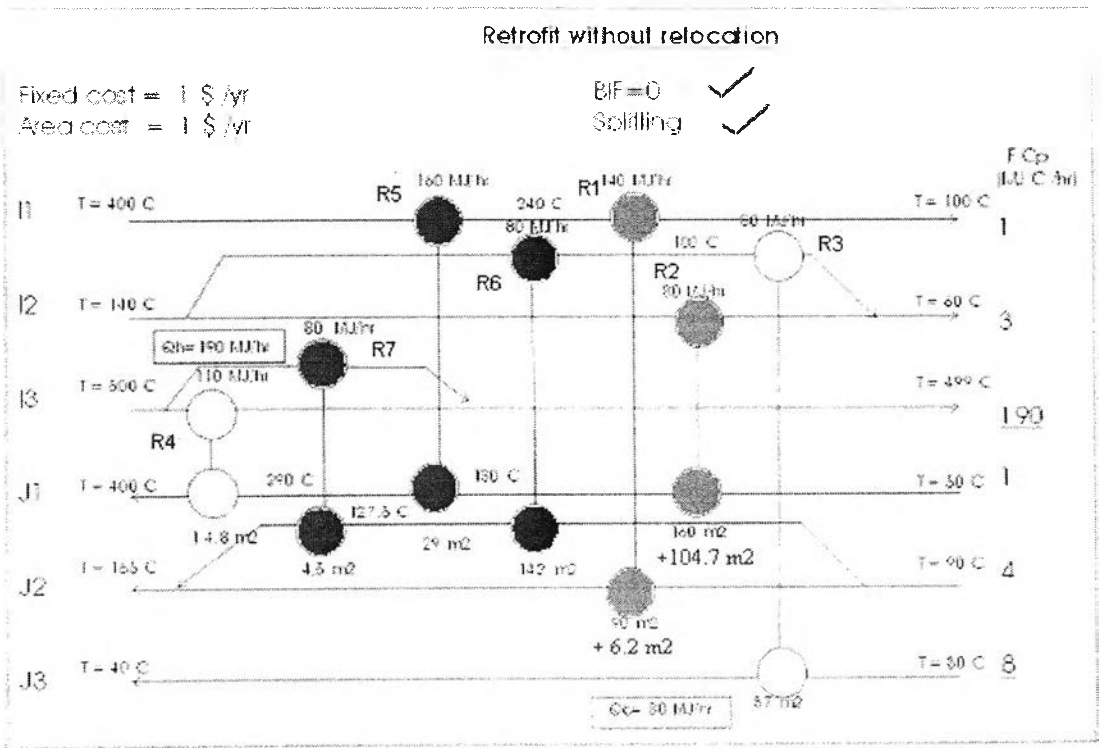

Figure 4.2 Retrofitting heat exchanger network (fixed cost=1 \$/yr and area cost=1\$/yr)

Table 4.6 Results of retrofit heat exchanger for case 4.1.1.1

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	cost $/yr
R1	140	84	90.2	6.2		6.2
R2	80	55	159.7	104.7		104.7
R3	80	66	37.6			
R4	110	26.2	14.8			
R5	160		29		29	29
R6	80		142		142	142
R7	80		4.5		4.5	4.5
Total		231.2	477.8	106.66%		286.4

Table 4.7 Total cost when fixed cost=1$/yr and area cost =1$/yr

Cost ($/yr)	Existing	Retrofit
Total utility cost	28860.8	19686.64
Total fixed and area cost		290.38
Total cost	28860.8	19977.02
Cost saving		8883.78
(%)		30.78%

New HEN is retrofit by adding area to heat exchanger R1 about 6.2 m² and heat exchanger R2 about 104.7 m². Three new heat exchangers (R5, R6, and R7) are added Hot utility is reduced from 270 MJ/hr to 190 MJ/hr and cold utility is reduced from 160 MJ/hr to 80 MJ/hr. Total cost was calculated and shown in Table 4.7. In this case (4.1.1.1) the minimum utilities from HEN can be found by GAMS software (Monica's equation) at maximum area. Therefore the minimum hot utility =190 MJ/hr and minimum cold utility =80 MJ/hr.

This retrofit case gave the same energy consumption as one designed by pinch technology as shown in Figure 4.3 because the fixed cost and area cost are very small composed to the utility cost.

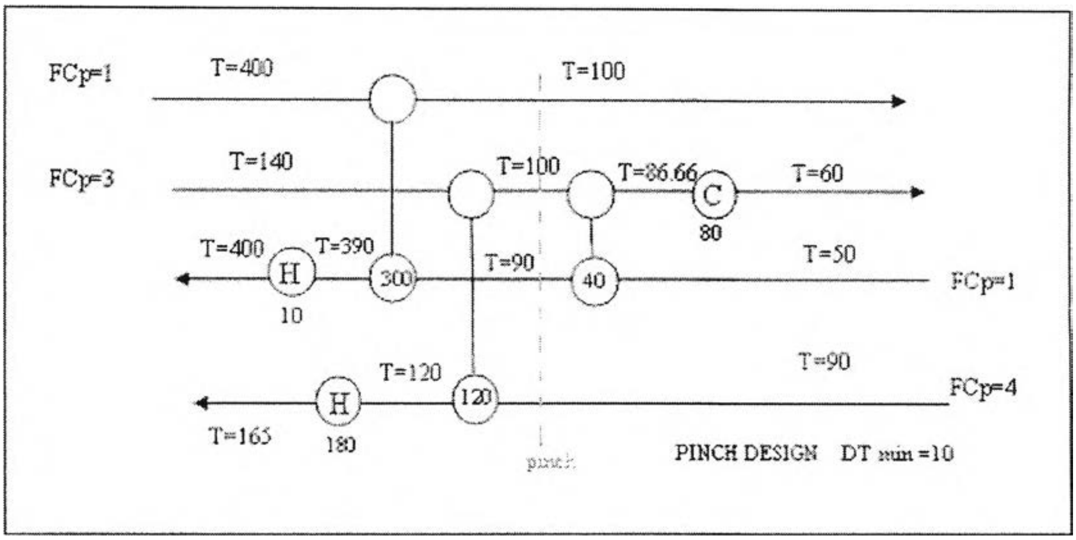

Figure 4.3 HEN which design by pinch technology.
Qh min= 190 MJ/hr, Qc min=80 MJ/hr

4.1.1.2 Retrofit without relocation when Fixed cost=1000 \$/yr and Area cost =20 \$/yr

This case is close to real condition where fixed cost =1000\$/yr and area cost =20 \$/yr with condition BIF=0 every streams can be split. Cost data for this case is shown in Table 4.8. The existing HEN is shown in Figure 4.1.Retrofitting HEN is shown in Figure 4.4

Table 4.8 Cost data for case study 4.1.1.2

Utilities	Cost \$/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost 1000+20 A \$/yr	

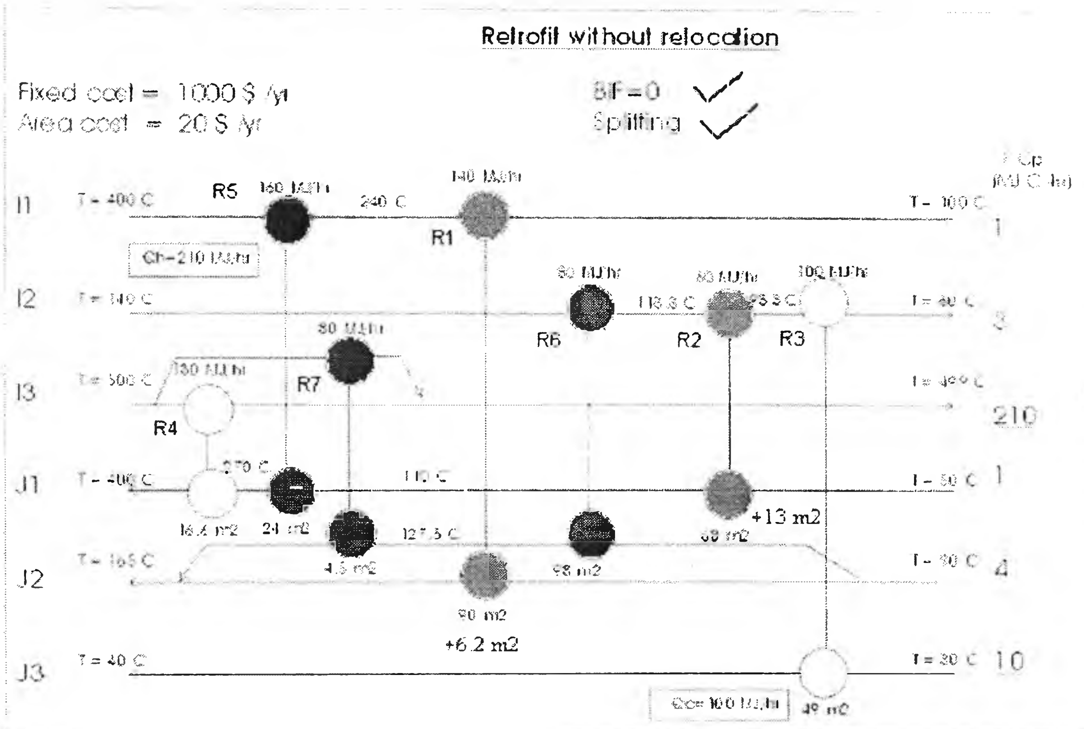

Figure 4.4 Retrofitting heat exchanger network (fixed cost=1000 and area cost=20 $/yr) Qh = 210MJ/hr, Qc = 100MJ/hr

New HEN is retrofit by adding new area at HEX R1 (I1, J2) = 6.2m², HEX R2 (I2, J1) = 13 m², and adding three new heat exchanger networks R5, R6 and R7. Hot utility is reduced from 270 MJ/hr to 210 MJ/hr and cold utility is reduced from 160 MJ/hr to 100 MJ/hr. Results of HEN retrofit are shown in Table4.9

Table 4.9 Results of retrofit heat exchanger for case 4.1.1.2

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	cost $/yr
R1	300	84	90.25	6.25		125
R2	80	55	68	13		260
R3	160	66	49			
R4	270	26.2	16.6			
R5	160		24.62		24.62	492.4
R6	80		98.2		98.2	1964
R7	80		4.53		4.53	90.6
Total		231.2	351.2	51.9%		2932

Table 4.10 Total cost when fixed cost=1000$/yr and area cost =20$/yr

Cost ($/yr)	Existing	Retrofit
Total utility cost	28860.8	21958.40
Total fixed and area cost		5932.68
Total cost	28860.8	27891.08
Cost saving		969.72
(%)		3.36%

The retrofit can save total cost about 969.72 $/yr or 3.36% from existing HEN as shown in Table 4.10. From the results the relationship between investment cost (fixed cost & area cost) and energy consumption are concluded in Table 4.10. When fixed cost and area cost are not significant by defining the small value (1 $/yr) in case 4.1.1.1. The retrofit design of case 4.1.1.1consume minimum utilities. In case 4.1.1.2 retrofit HEN consume larger hot and cold utilities than case 4.1.1.1 because GAMS software trade off between cost of investment cost (adding new HEX or adding new area) and the utility cost.

4.1.2 Study Relationship between Investment Cost (fixed cost& area cost) and Energy Consumption in Retrofit HEN when Increasing Flow Rate 10 Times.

In this case the effect with retrofitting HEN was studied when increasing flow rate 10 times. Relationship between investment cost (Fixed cost & Area cost) and energy consumption was studied when increasing flow rate 10 times. The Existing heat exchanger network is shown in Figure 4.5. Stream properties of existing HEN is shown in Table 4.11 and Properties of HEX of existing HEN is shown in Table 4.12

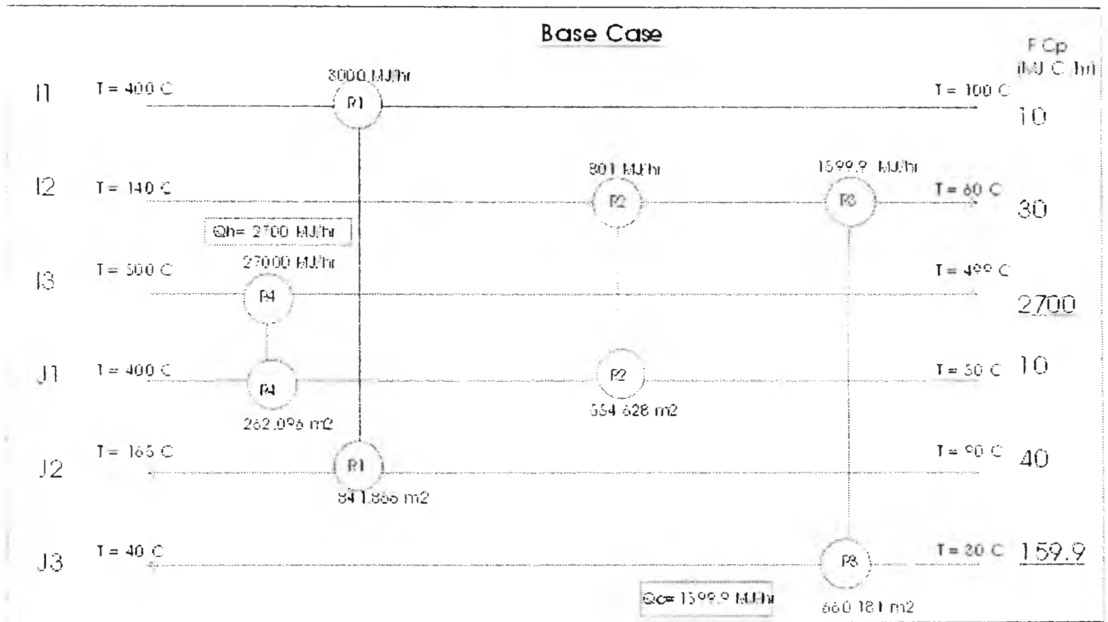

Figure 4.5 Existing heat exchanger network (BASE CASE)
Qh = 2700 MJ/hr, Qc = 1599.9 MJ/hr

Table 4.11 Properties of stream of existing HEN

Stream	F (Ton/hr)	Cp (kJ/kg-°C)	h (MJ/h-m²-°C)	Tin (°C)	Tout (°C)
I1	10	1	0.1	400	100
I2	30	1	0.1	140	60
I3	2700	1	0.1	500	499
J1	10	1	0.1	50	400
J2	40	1	0.1	90	165
J3	159.9	1	0.1	30	40

Table 4.12 Properties of HEX of existing HEN

HEX	Q (MJ/hr)	Existing area (m²)
R1	3000	841.8
R2	801	554.6
R3	1599.9	660.1
R4	2700	262.0

Table 4.13 Total cost of existing HEN

Case	Hot utility MJ/hr	Cold utility MJ/hr	Operating Cost ($/yr)	Total cost ($/yr)
BIF=0, Splitting	2700	1599	288588.00	288588.00

Total cost of existing HEN is calculated, which is shown in Table 4.13. In this case only operating cost is considered and not economical network. It need to be approved by retrofit existing HEN.

4.1.2.1 Retrofit without relocation when Fixed cost=1 $/yr and Area cost =1 $/yr when increasing flow rate 10 times

Relationship between investment cost (Fixed & area cost) and energy consumption is studied. When fixed cost =1 $/yr and area cost =1 $/yr in condition (BIF=0) only one exchanger is allowed for the same hot-cold-stream matching and every streams can be split. And cost data for case 4.1.2.1 is shown in Table 4.14. Existing HEN, shown in Figure 4.5 is the base case. The retrofit network is shown in Figure 4.6.

Table 4.14 Cost data for case 4.1.2.1

Utilities	Cost $/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost(1)+(1) A $/yr	

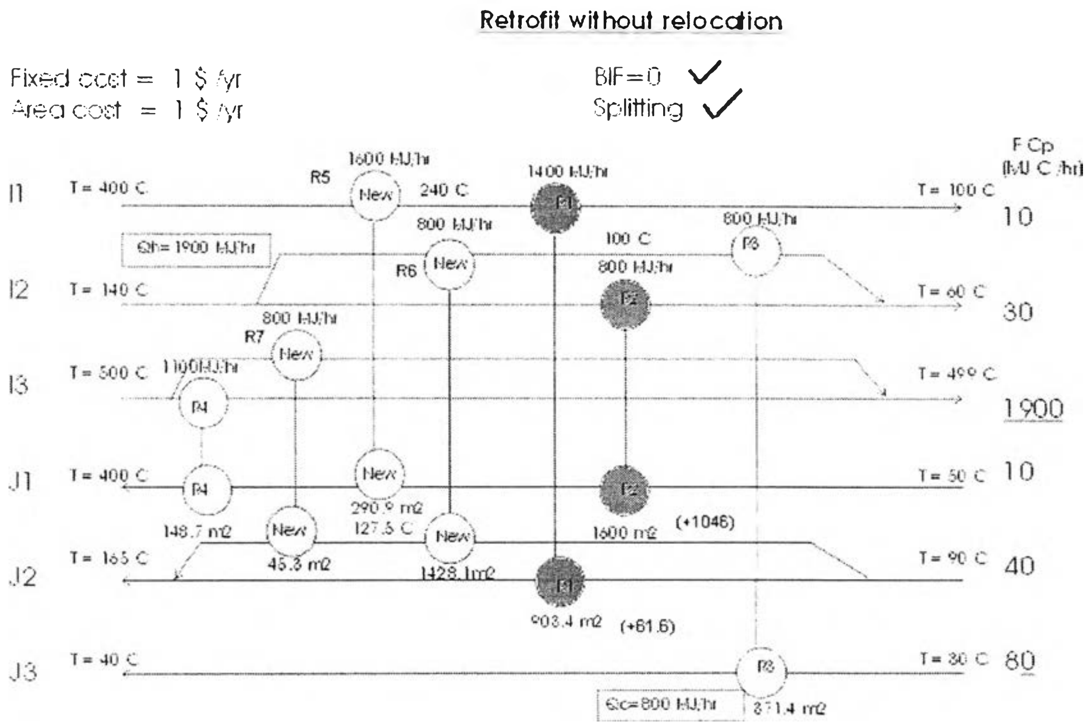

Figure 4.6 Retrofitting heat exchanger network (fixed cost=1and area cost=1 $/yr)
Qh = 1900MJ/hr, Qc = 800MJ/hr

Table 4.15 Results of retrofit heat exchanger for case 4.1.2.2

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	cost $/yr
R1	1400	841.8	903.4	61.618		61.6
R2	800	554.6	1600.6	1046		1046.0
R3	800	660.1	371.4			0.0
R4	1100	262	148.7			0.0
R5	1600		290.9		290.9	290.9
R6	800		1428.1		1428.1	1428.1
R7	800		45.3		45.3	45.3
Total		2318.5	4788.5	106.53%		2872.0

Table 4.16 Total cost when fixed cost=1$/yr and area cost =1$/yr

Cost ($/yr)	Existing	Retrofit
Total utility cost	288588	196576.00
Total fixed and area cost		2874.98
Total cost	288588	199450.98
Cost saving (%)		30.89%

In this case 4.1.2.1 the minimum utilities from HEN designed by GAMS software (Monica's equation) at maximum heat transfer, are 1900 MJ/hr and 800 MJ/hr for hot and cold utilities respectively.

4.1.2.2 Retrofit without relocation when Fixed cost=1000 $/yr and Area cost =20 $/yr when increasing flow rate 10 times

This case is the close to real condition with the fixed cost =1000$/yr and area cost =20 $/yr under the condition (BIF=0) and every streams can be split. Cost data for this case is shown in Table 4.17. Retrofitting HEN is shown in Figure 4.7.

Table 4.17 Cost data for case 4.1.2.2

Utilities	Cost $/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost 1000+20 A $/yr	

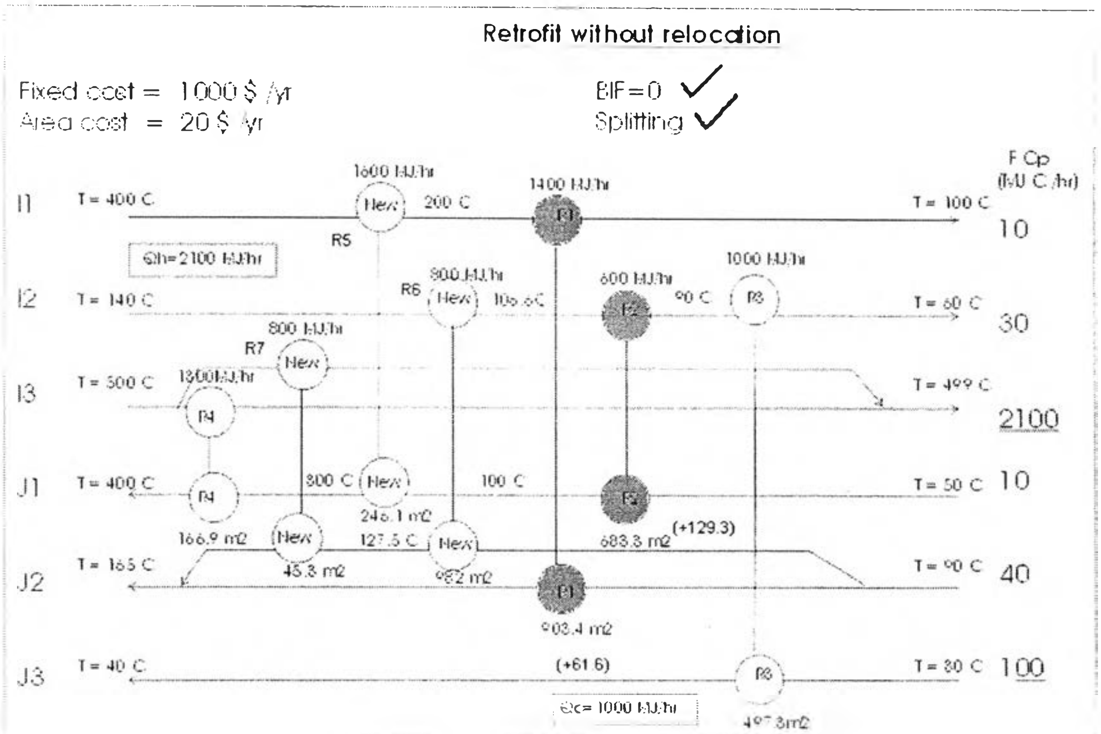

Figure 4.7 Retrofitting heat exchanger network (fixed cost=1000 and area cost=20 $/yr) Qh = 2100MJ/hr, Qc = 1000MJ/hr

HEN is retrofit by adding new area to HEX R1 (I1, J2) about 61.6m², HEX R2 (I2, J1) about 129.3 m², and adding three new heat exchanger networks R5, R6 and R7. Hot utility is reduced from 2700 MJ/hr to 2100 MJ/hr and cold utility is reduced from 1599 MJ/hr to 1000 MJ/hr. Results of retrofit HEN are shown in Table4.18

Table 4.18 Results of retrofit heat exchanger for case 4.1.2.2

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	cost $/yr
R1	1400	841.8	903.4	61.6		1232.0
R2	600	554.6	683.9	129.3		2586.0
R3	1000	660.1	497.3			0.0
R4	1300	262	166.9			0.0
R5	1600		246.1		246.1	4922.0
R6	800		982.0		982.0	19640.0
R7	800		45.3		45.3	906.0
Total		2318.5	3524.9	52.03%		29286.0

Table 4.19 Total cost when fixed cost=1000$/yr and area cost =20$/yr

Cost ($/yr)	Existing	Retrofit
Total utility cost	288588	219584.00
Total fixed and area cost		32289.74
Total cost	288588	251873.74
Cost saving		36714.26
(%)		12.72%

Retrofitting HEN shown in Table 4.19 can save total cost about 36714.26 $/yr or 12.72% saving from existing HEN. The trend of heat exchanger networks design are the same at same fixed cost and area cost for both normal stream flow rates and 10 times flow rate.

4.2 Retrofit with relocation

4.2.1 Study Relationship between Investment Cost (fixed & area cost) and Energy Consumption

4.2.1.1 Retrofit with relocation when Fixed cost=1$/yr and Area cost =1 $/yr

Relationship between investment cost (Fixed & area cost) and energy consumption was studied. Fixed cost =1 $/yr and area cost =1 $/yr in condition (BIF=0) only one exchanger is allowed for the same hot-cold-stream matching and every streams can be split. In this case existing HEN shown in Figure 4.1 is used. And cost data for case 4.2.1.1 shown in Table 4.20 is used. The retrofit network is shown in Figure 4.8

Table 4.20 Cost data for case 4.2.1.1

Utilities	Cost $/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost(1)+(1) A $/yr	

Existing heat exchangers is switched position before adding new area or adding new heat exchanger. In this case the new position of heat exchangers is shown in Figure 4.8 following heat exchanger's name, compared to existing heat exchanger network (Figure 4.1).

- Heat exchanger R1 is switched from I1,J2 to I2,J2
- Heat exchanger R2 stay is the same position I2,J1
- Heat exchanger R3 is switched from I2,J3 to I1,J2
- Heat exchanger R4 is switched from I3,J1 to I2J3

Retrofit with relocation of heat exchanger network is shown in Figure 4.8

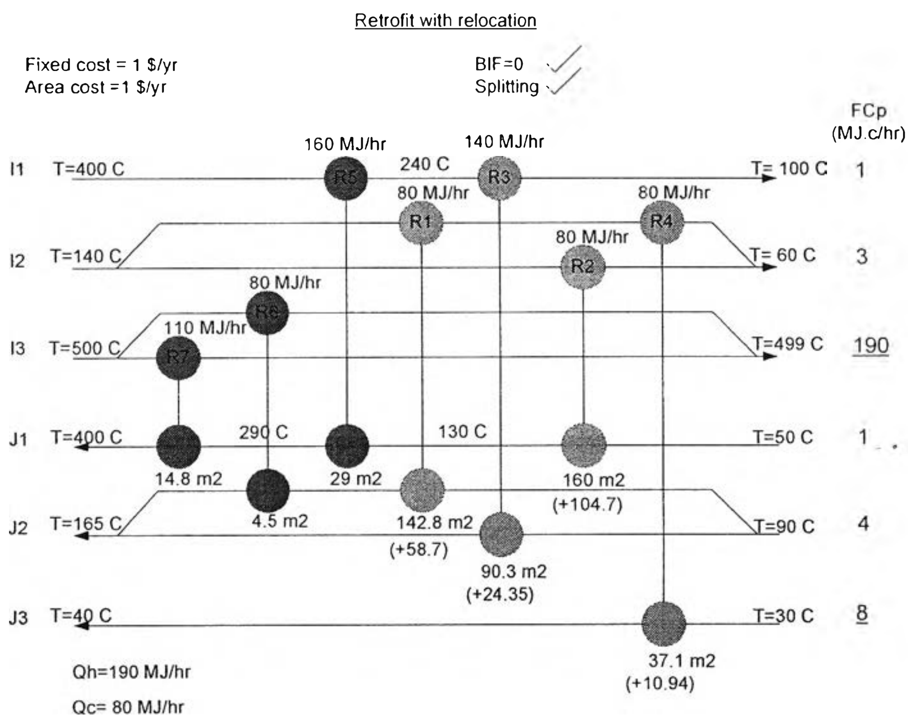

Figure 4.8 Retrofitting with relocation heat exchanger network (fixed cost=1 and area cost=1 $/yr) Qh = 190MJ/hr, Qc= 80MJ/hr

Table 4.21 Results heat exchanger retrofit for case 4.2.1.1

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	cost $/yr
R1	80	84.1	142.8	58.7		58.7
R2	80	55.3	160	104.7		104.7
R3	140	66	90.3	24.3		24.3
R4	80	26.2	37.1	10.9		10.9
R5	160		29		29	29
R6	80		4.5		4.5	4.5
R7	110		14.8		14.8	14.8
Total		231.6	478.5	106.61%		246.9

Table 4.22 Total cost when fixed cost=1$/yr and area cost =1$/yr

Cost ($/yr)	Existing	Retrofit
Total utility cost	28860.8	19657.60
Total fixed and area cost		250.20
Total cost	28860.8	19907.80
Cost saving		8953.00
(%)		31.02%

In this case (4.2.1.1) the minimum utilities from HEN designed by GAMS software (Monica's equation) at maximum heat transfer, 190 MJ/hr and 80 MJ/hr for hot and cold utilities respectively.

4.2.1.2 Retrofit with relocation when Fixed cost=1000$/yr and Area cost =20 $/yr

This case is normal condition fixed cost =1000$/yr and area cost =20 $/yr in condition BIF=0 and every streams can be split. Cost data for this case is shown in Table 4.23. Retrofitting HEN is shown in Figure 4.9.

Table 4.23 Cost data for case 4.2.1.2

Utilities	Cost $/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost 1000+20 A $/yr	

Existing heat exchangers is switched position before adding new area or adding new heat exchanger. In this case the new position of all existing heat exchangers is shown in Figure 4.9 following heat exchanger's name when compared with existing heat exchanger network (Figure 4.1).

- Heat exchanger R1 stay the same position I1,J2
- Heat exchanger R2 is switched from I2,J1 to I2,J3
- Heat exchanger R3 is switched from I2,J3 to I2,J1
- Heat exchanger R4 stay the same position I3,J1

Retrofit with relocation of heat exchanger network is shown in Figure 4.9

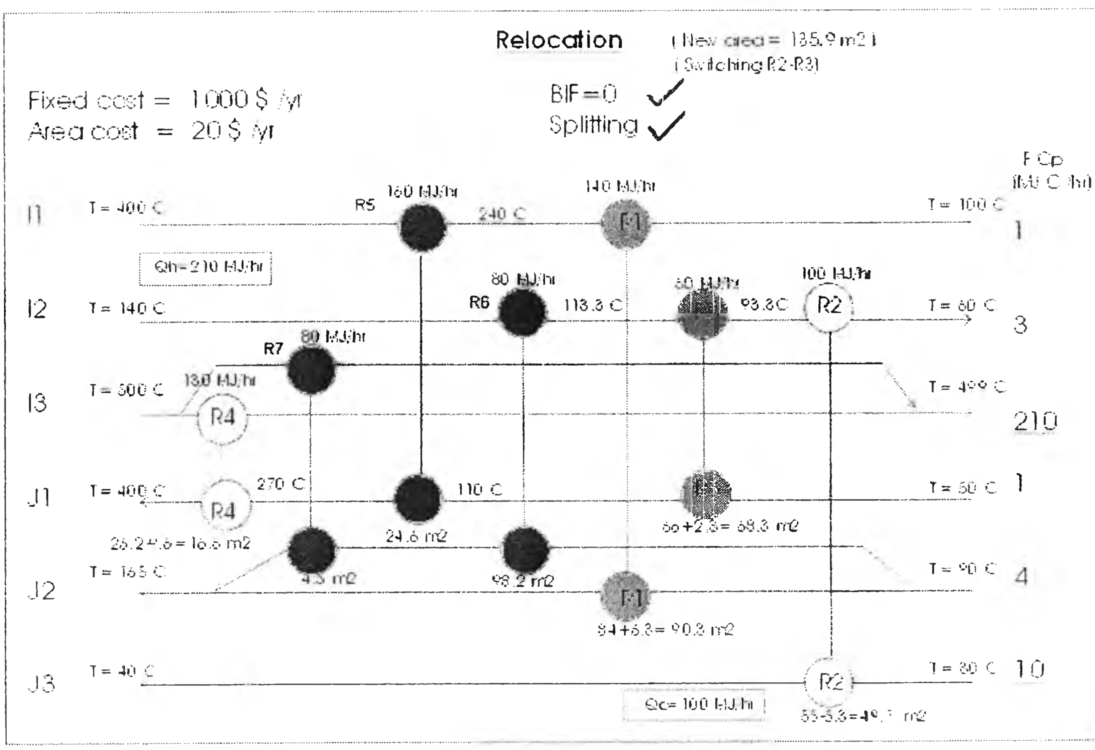

Figure 4.9 Retrofitting with relocation heat exchanger network (fixed cost=1000and area cost=20 $/yr) Qh = 210MJ/hr, Qc = 100MJ/hr

Table 4.24 Results of retrofit heat exchanger for case 4.2.1.2

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	cost $/yr
R1	140	84.1	90.4	6.3		126
R2	100	55.3	49.7			
R3	60	66	68.3	2.3		46
R4	130	26.2	16.6			
R5	160		24.6		24.6	492
R6	80		98.2		98.2	1964
R7	80		4.5		4.5	90
Total		231.6	352.3	52.12%		2718

Table 4.25 Total cost when fixed cost=1000$/yr and area cost =20$/yr

Cost ($/yr)	Existing	Retrofit
Total utility cost	28860.8	21958.40
Total fixed and area cost		5718.68
Total cost	28860.8	27677.08
Cost saving		1183.72
(%)		4.10%

Retrofitting HEN in Table 4.25 can save total cost 1183.72 $/yr or 4.10% saving from existing HEN.

4.2.2 Study Relationship between Investment Cost (fixed cost& area cost) and Energy Consumption when increasing flow rate 10 times

In this case the effect of retrofitting HEN was studied, when increase flow rate 10 times. Relationship between investment cost (fixed cost & area cost) and energy consumption was studied.

4.2.2.1 Retrofit with relocation when Fixed cost=1$/yr and Area cost =1 $/yr when increasing flow rate 10 times

Relationship between investment cost (fixed & area cost) and reducing energy consumption is studied. When fixed cost =1 $/yr and area cost =1 $/yr under condition (BIF=0) only one exchanger is allowed for the same hot-cold-stream matching and every streams can be split. The utilities of the existing HEN shown in Figure 4.5 are Qh = 2700 MJ/hr, Qc = 1599.9 MJ/hr. Cost data for case 4.2.2.1 is shown in Table 4.26. The network is shown in Figure 4.10.

Table 4.26 Cost data for case 4.2.2.1

Utilities	Cost $/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost(1)+(1) A $/yr	

Existing heat exchangers is switched position before adding new area or adding new heat exchanger. In this case the new position of all existing heat exchangers is shown in Figure 4.10 following heat exchanger's name when compared to existing heat exchanger network (Figure 4.5).

- Heat exchanger R3 is switched from I2,J3 to I1,J2
- Heat exchanger R1 is switched from I1,J2 to I2,J1
- Heat exchanger R2 is switched from I2,J1 to I2,J2
- Heat exchanger R4 is switched from I3,J1 to I2,J3

Retrofit with relocation of heat exchanger network is shown in Figure 4.10

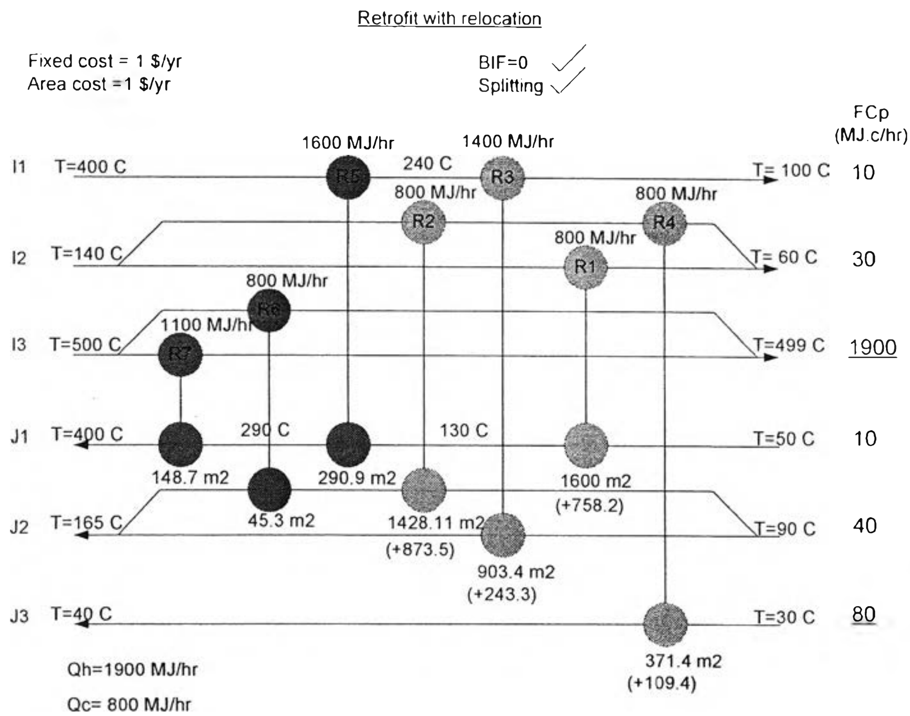

Figure 4.10 Retrofitting with relocation heat exchanger network (fixed cost=1and area cost=1 $/yr)Qh = 1900MJ/hr, Qc = 800MJ/hr

Table 4.27 Results of retrofit heat exchanger for case 4.2.2.1

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	cost $/yr
R1	1400	841.8	1600	758.2		758.2
R2	600	554.6	1428.1	873.5		873.5
R3	1000	660.1	903.4	243.3		243.3
R4	1300	262	371.4	109.4		109.4
R5	1600		290.9		290.9	290.9
R6	800		45.3		45.3	45.3
R7	800		148.7		148.7	148.7
Total		2318.5	4787.8	106.50%		2469.3

Table 4.28 Total cost when fixed cost=1$/yr and area cost =1$/yr when increase flow rate 10 times.

Cost ($/yr)	Existing	Retrofit
Total utility cost	288588	196576.00
Total fixed and area cost		2473.00
Total cost	288588	199049.00
Cost saving (%)		89539.00 31.03%

In this case (4.2.2.1) the minimum utilities from HEN designed by GAMS software (Monica's equation) at maximum heat transfer are 1900 MJ/hr and 800 MJ/hr for hot and cold utilities respectively.

4.2.2.2 Retrofit with relocation when Fixed cost=1000$/yr and Area cost =20 $/yr when increasing flow rate 10 times

Relationship between investment cost (fixed & area cost) and energy consumption is studied. In normal condition when fixed cost =1000 $/yr and area cost =20 $/yr in condition (BIF=0) only on exchanger is allowed for the same hot-cold-stream matching) and every streams can be split. This case (4.2.2.2) we use existing HEN shown in Figure 4.5 has Qh = 2700 MJ/hr, QC = 1599.9 MJ/hr. Cost data for case 4.2.2.2 is shown in Table 4.29. The network is shown in Figure 4.11.

Table 4.29 Cost data for case 4.2.2.2

Utilities	Cost $/(MJ/hr-yr)
I3	95.04
J3	20
Heat Exchanger Cost(1000)+(20) A $/yr	

Existing heat exchangers is switched position before adding new area or adding new heat exchanger. In this case the new position of all existing heat exchangers is shown in Figure 4.11 following heat exchanger's name when compared to existing heat exchanger network (Figure 4.5).

- Heat exchanger R1 is switched from I1,J2 to I2,J2
- Heat exchanger R2 stay the same position I2,J1
- Heat exchanger R3 is switched from I2,J3 to I1,J2
- Heat exchanger R4 is switched from I3,J1 to I2,J3

Retrofit with relocation of heat exchanger network is shown in Figure 4.11

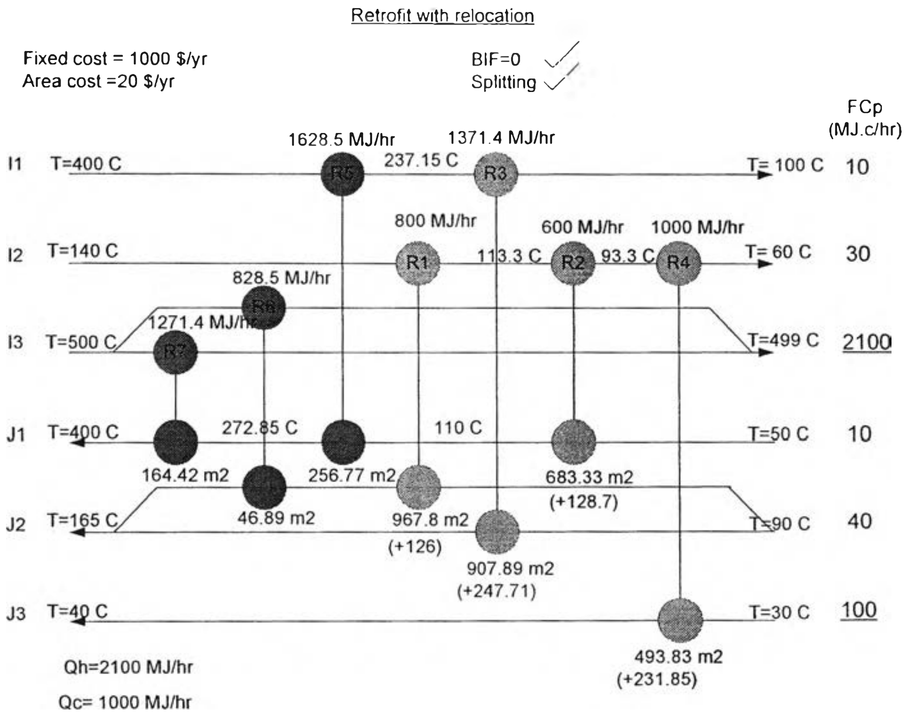

Figure 4.11 Retrofitting with relocation heat exchanger network (Fixed cost=1000and Area cost=20 $/yr) Qh = 2100MJ/hr, Qc = 1000MJ/hr

Table 4.30 Results of retrofit heat exchanger for case 4.2.2.2

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	cost $/yr
R1	1400	841.8	967.8	126		2520
R2	600	554.6	683.3	128.7		2574
R3	1000	660.1	907.9	247.8		4956
R4	1300	262	493.8	231.8		4636
R5	1600		256.7		256.7	5134
R6	800		46.8		46.8	936
R7	800		164.4		164.4	3288
Total		2318.5	3520.7	51.85%		24044

Table 4.31 Total cost when fixed cost=1000$/yr and area cost =20$/yr when increase flow rate 10 times.

Cost ($/yr)	Existing	Retrofit
Total utility cost	288588	219584.00
Total fixed and area cost		27059.26
Total cost	288588	246643.26
Cost saving (%)		41944.74 14.53%

The retrofit saved total cost about 41944.74 \$/yr or 14.53% from existing HEN as shown in Table 4.31. The trend of heat exchanger networks design are the same at same fixed cost and area cost for the normal flow rate and 10 times flow rate stream. Relationship between investment cost (fixed cost & area cost) and energy consumption is concluded. When fixed cost and area cost was small value (fixed cost =1 \$/yr and area cost =1 \$/yr). The retrofit design consumes minimum hot and cold utilities. In case 4.2.2.2 retrofit HEN consume higher hot and cold utilities than ones of case 4.2.21 because GAMS software trades off between cost of adding new HEX or adding new area which are investment cost and the utility cost .

4.3 Retrofit with/without Relocation of Heat Exchanger Networks for Crude Refinery Unit

The GAMS model for retrofit can be applied for crude refinery.The pump around's equation is added to Monica's GAMS model (retrofit with/without relocation). Two retrofit techniques are used to solve this problem. They are retrofit without relocation and retrofit with relocation. In this case Ji's Pro II model of crude fractionation column is used with light crude as feed strean. The properties of crude of API gravity, TBP and light-end composition are shown in Table 4.32, 4.33 and 4.34

Table 4.32 Feedstock used for design (Bagajewicz and Ji, 2001)

Crude	density (kg/m³)	throughput (m³/hr)
Light crude	845 (36.0 API)	795

Table 4.33 TBP data (Bagajewicz and Ji, 2001)

vol%	temperature (˚C) Light crude
5	45
10	82
30	186
50	281
70	382
90	552

Table 4.34 Light-end composition of crude (Bagajewicz and Ji, 2001)

component	vol% Light crude
ethane	0.13
propane	0.78
isobutene	0.49
n-butane	1.36
isopentane	1.05
n-pentane	1.3
Total	5.11

Table 4.35 Results for light crude

	flow rate (tone/hr)			Duty of PA (10^6 J/hr)				Steams of side stripping (tone/hr)		
case	I1(PA 1)	I2(PA 2)	I3(PA 3)	PA1	PA2	PA3	total	5.0	4.0	3.0
1.0	733.1	85.1	42.2	130000.0	20000.0	8000.0	158000.0	1.6	2.5	3.0
2.0	680.8	127.7	44.9	120000.0	29500.0	8500.0	158000.0	1.9	2.6	3.0
3.0	575.9	180.9	97.3	100000.0	40000.0	18000.0	158000.0	2.5	3.3	3.0
4.0	522.8	208.4	125.8	90000.0	45000.0	23000.0	158000.0	3.0	3.7	3.1
5.0	442.7	233.0	197.3	75000.0	48000.0	35000.0	158000.0	3.7	4.8	3.1
6.0	304.5	315.1	280.8	50000.0	60000.0	48000.0	158000.0	5.7	6.7	3.1
7.0	188.4	397.3	351.3	30000.0	70000.0	58000.0	158000.0	8.2	8.7	3.2

To find the relationship between duty of each pump-around and steam of side stripper, Table 4.35 shows the results of changing duty of each pump-around with the steam flow rate of each side stripper with the constant total duty of pump-around at 158,000 MJ/hr. From the result of Table 4.35 the regression gives the relation function between duty of pump-around and steam of side stripper as shown in Table 4.36

Table 4.36 Relationship between duty of pump-around (PA1, PA2, PA3) and steam of side stripper (y) for light crude

y=a(PA1)+b(PA2)+c(PA3)+d

R Square	Steam of side stripping	a	b	c	d
0.922109	5	2.30672E-05	2.71811E-05	0.000138409	-3.27933
0.965398	4	0.000107082	9.60154E-05	0.000234243	-15.4108
0.962669	3	6.62062E-05	6.8839E-05	6.75194E-05	-7.55178

From the modified Ji's model of crude fractionation column, the stream data relationship shown in Table 4.37 is used to find the heat exchanger network by MILP model.

Table 4.37 Stream data of light crude type

Stream	Flow (tone/hr)	Tin ©	Tout ©
I1	177.82	43.333	21.111
I3	120.15	219.68	21.111
I5	59.199	270.65	21.111
I7	102.41	318.51	21.111
I8	211.7	348.18	260
I2		182.57	104.44
I4		268.78	173.62
I6		308.51	232.22
I9		399	499
J1	752.59	21.111	137.77
J2	673.42	137.78	360
J3		20	30

The heat capacity in this problem is shown in the function of temperature found by using liner regression. The function of heat capacity is shown in Table 4.38.

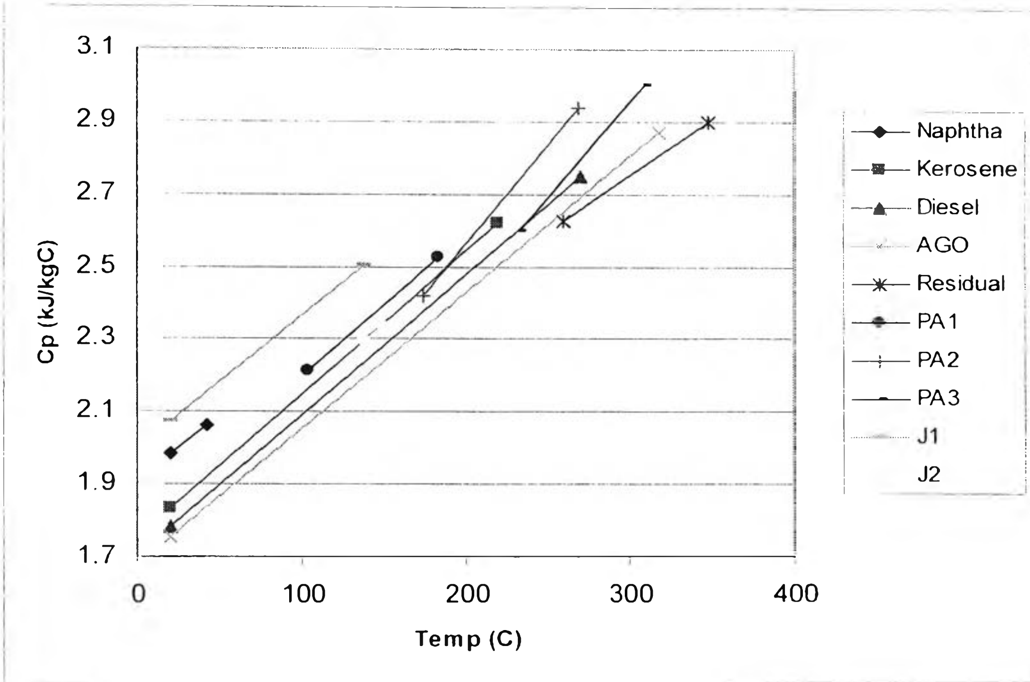

Figure 4.12 Changing of heat capacity with temperature for light crude.

Table 4.38 Function of heat capacity for light crude

Stream	Heat capacity	
I1	Cp =	(0.0035(T))+1.9098
I3	Cp =	(0.004(T))+1.7483
I5	Cp =	(0.0039(T))+1.7044
I7	Cp =	(0.0038(T))+1.6756
I8	Cp =	(0.0031(T))+1.8201
I2	Cp =	(0.004(T))+1.7979
I4	Cp =	(0.0055(T))+1.4682
I6	Cp =	(0.0052(T))+1.3834
I9	Cp =	4.18
J1	Cp =	(0.0037(T))+1.9966
J2	Cp =	(0.0035(T))+1.8143
J3	Cp =	4.18

Utility and heat exchanger costs for crude fractionation unit are shown in Table 4.39. Costs of stripper steam are shown in Table 4.40.

Table 4.39 Utility and heat exchanger cost for crude fractionation unit

Utilities	Cost $/(MJ/hr-yr)
I9	19.75
J3	1.861
Heat Exchanger Cost 5291.9+77.788 A $/yr	

Table 4.40 Cost of stripper steam

Steam stripper	Cost $/(MJ/hr-yr)
SS1	20.33
SS2	20.33
SS3	20.33

The existing heat exchanger network of crude refinery unit is designed from data Table 4.32 to 4.40, shown in Figure 4.13. Properties of existing HEN are shown in Table 4.41.

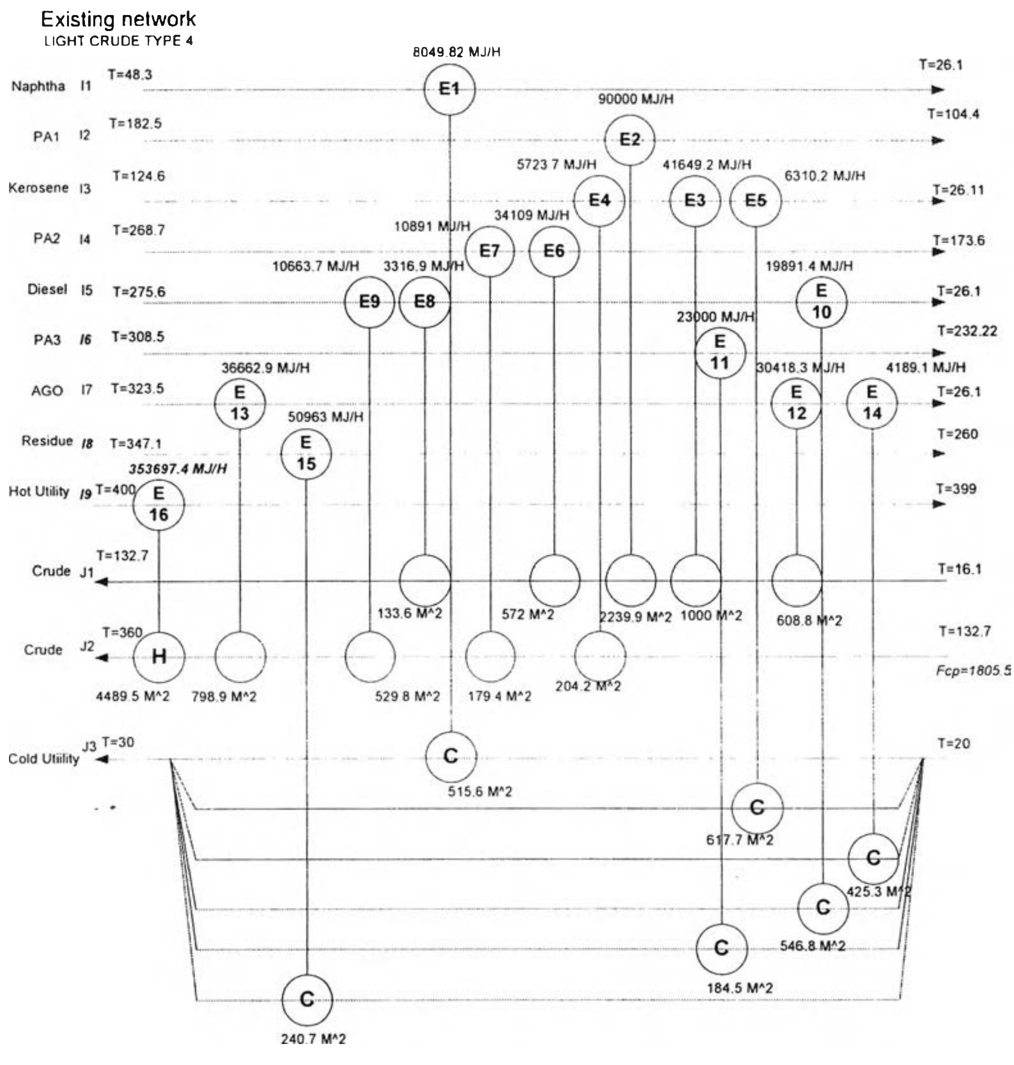

Figure 4.13 Existing HEN of crude refinery unit

Table 4.41 Properties of existing HEN

Stream	Flow (tone/hr)	Tin ©	Tout ©
I1	177.82	43.333	26.11
I3	120.15	124.6	26.11
I5	59.199	275.6	26.11
I7	102.41	323.5	26.11
I8	211.7	348.18	260
I2		182.57	104.44
I4		268.78	173.62
I6		308.51	232.22
I9		399	499
J1	752.59	16.11	132.7
J2	673.42	132.7	360
J3		20	30

Data from Table 4.39 and 4.40 are used to calculate total cost of existing HEN shown in Table 4.42

Table 4.42 Total cost of existing HEN of crude refinery unit

Case	Hot utility MJ/hr	Cold utility MJ/hr	Capital Cost ($/yr)	Operating Cost ($/yr)	Total cost ($/yr)
BIF=0, Splitting	353697.5	112404	0.00	7194849.73	7194849.73

The operating cost of existing HEN were 7194849.73$/yr which is not economical the retrofit model can be applied to this existing HEN to reduce these costs.

4.3.1 Retrofit without Relocation Applied for Crude Fractionation Unit

In case 4.3.1 the retrofit without relocation was applied to existing HEN. Using data from Table 4.40 and 4.41 for calculating total cost of retrofit HEN. Retrofit without relocation of HEN of crude refinery is shown in Figure 4.14.

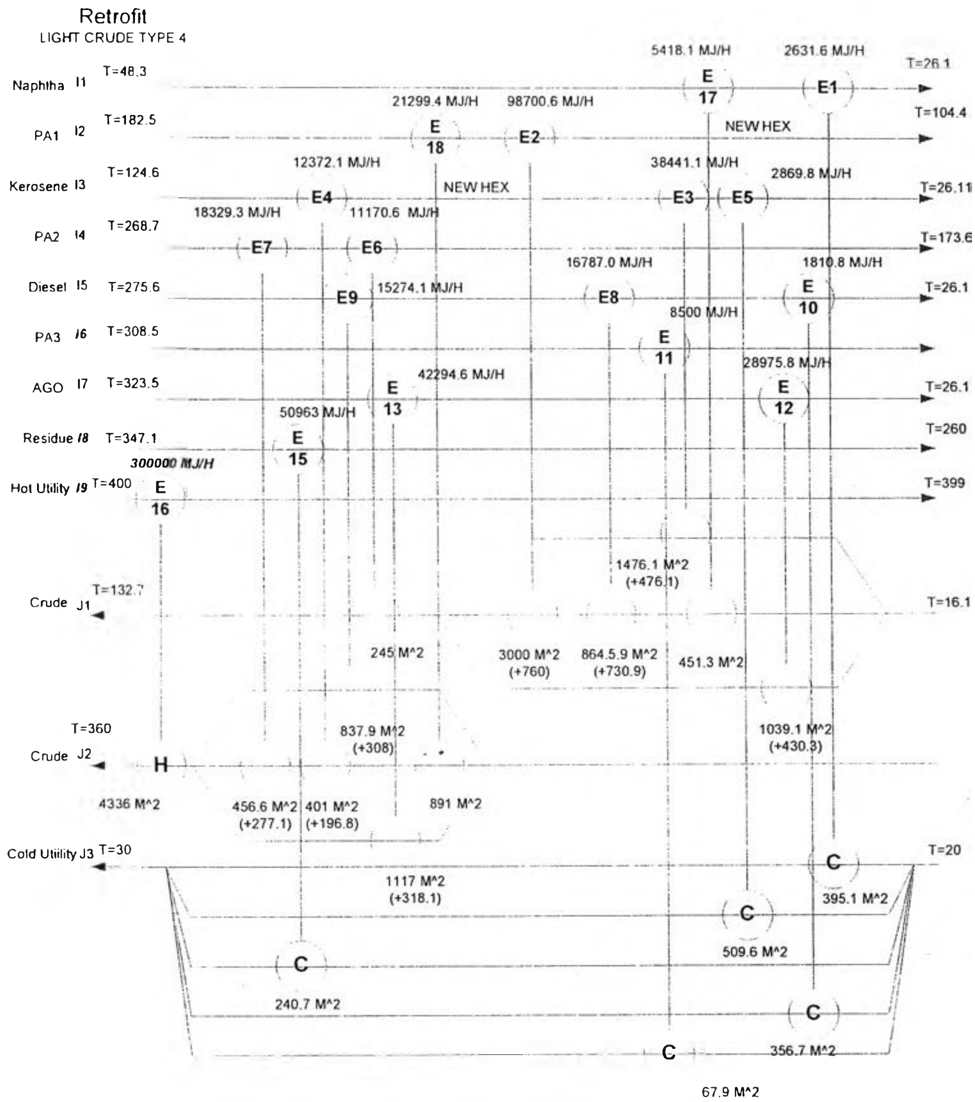

Figure 4.14 Retrofit without relocation HEN of crude refinery

Retrofit without relocation of heat exchanger network was done by adding new area shown in Table 4.43.

Table 4.43 Results of retrofit without relocation HEN of light crude refinery unit

HE	Retrofit load kW	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	Cost $
E1	2631.6	515.6	395.1			
E2	98700.6	2239.9	3000	760.1		130281.14
E3	38441.1	1000	1476.1	476.1		81603.54
E4	12372.1	204.2	401	196.8		33731.52
E5	2869.8	617.7	509.6			
E6	11170.6	572	245			
E7	18329.3	179.4	456.6	277.2		47512.08
E8	16787	133.6	864.5	730.9		125276.26
E9	15274.1	529.8	837.9	308.1		52808.34
E10	1810.8	546.8	356.7			
E11	8500	184.5	67.9			
E12	28975.8	608.8	1039.1	430.3		73753.42
E13	42294.6	798.9	1117	318.1		54522.34
E14		425.3				
E15	50963	240.7	240.7			
E16	300000	4711.4	4336			
E17	5418.1		451.3		451.3	77352.82
E18	21299.4		891		891	152717.4
Total		13508.6	16685.5	23.5%		829558.86

Two new heat exchanger networks R17 and R18 were added. The HEX R14 is not used .Hot utility is reduced from 353697.5 MJ/hr to 300000 MJ/hr and cold utility is reduced from 112404 MJ/hr to 66775.45 MJ/hr. about 4.24 % cost saving as shown in Table 4.44.

Table 4.44 Annual cost comparison between original and retrofit network for light crude

Cost ($/yr)	Existing	Retrofit
Total utility cost	7194849.7	6049379.59
Total fixed and area cost		840183.11
Total cost	7194849.7	6889562.70
Cost saving		305287.03
(%)		4.24%

4.3.2 Retrofit with Relocation Applied for Crude Fractionation Unit

In case 4.3.2 retrofit with relocation was applied to existing HEN. Using data from Table 4.39and 4.40 to calculate total cost of retrofitting HEN. Retrofit with relocation HEN of crude refinery unit is shown in Figure 4.15. Existing heat exchangers is switched position before adding new area or adding new heat exchanger. In this case the new position of all existing heat exchangers is shown in Figure 4.15 following heat exchanger's name comparing to existing heat exchanger network (Figure 4.13).

- Heat exchanger E1 is located at I1,J3
- Heat exchanger E2 is located at I2,J1
- Heat exchanger E3 is switched from I3,J1 to I8,J2
- Heat exchanger E4 is switched from I3,J2 to I4,J1
- Heat exchanger E5 is switched from I3,J3 to I3,J1
- Heat exchanger E6 is switched from I4,J1 to I5,J1
- Heat exchanger E7 is switched from I4.J2 to I3,J3
- Heat exchanger E8 is switched from I5,J1 to I7,J3
- Heat exchanger E9 is switched from I5,J2 to I5,J2
- Heat exchanger E10is switched from I5,J3 to I4,J2
- Heat exchanger E11is switched from I6,J3 to I5.J3
- Heat exchanger E12 is switched from I7,J1 to I7,J2
- Heat exchanger E13 is switched from I7,J2 to I7,J1
- Heat exchanger E14 is switched from I7,J3 to I6,J2
- Heat exchanger E15 is switched from I8,J3 to I3,J2
- Heat exchanger E16 is located at I9,J2

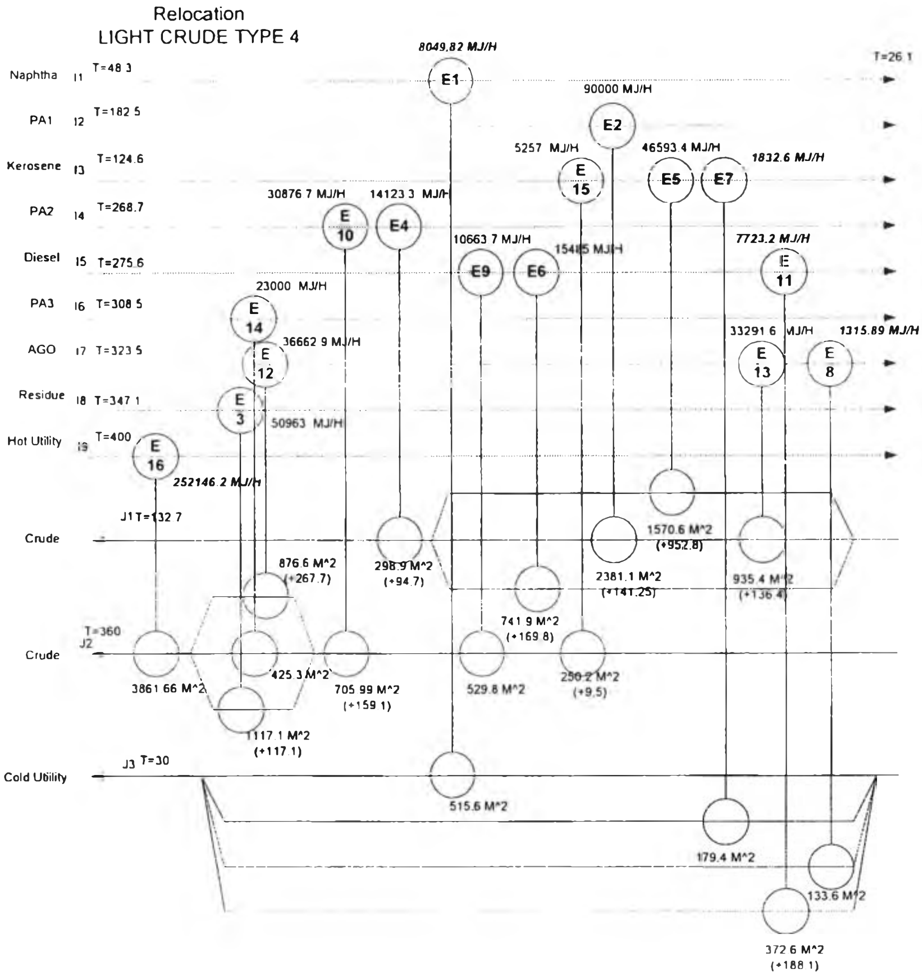

Figure 4.15 Retrofit with relocation HEN of crude refinery unit

Table 4.45 Results of retrofit with relocation HEN of light crude refinery unit

HE	Retrofit load MJ/hr	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	Cost $
E1	8049.8	515.6	515.6			
E2	90000	2239.9	2381.1	141.2		24201.68
E3	50963	1000	1117.1	117.1		20070.94
E4	14123.3	204.2	298.9	94.7		16231.58
E5	46593	617.7	1570.6	952.9		163327.06
E6	15485	572	741.9	169.9		29120.86
E7	1832.6	179.4	179.4			
E8	1315.9	133.6	133.6			
E9	10663.7	529.8	529.8			
E10	30876.7	546.8	705.99	159.19		27285.166
E11	7723.2	184.5	372.6	188.1		32240.34
E12	36662.9	608.8	876.6	267.8		45900.92
E13	33291.6	798.9	935.4	136.5		23396.1
E14	23000	425.3	425.3			
E15	5257	240.7	250.2	9.5		1628.3
E16	252146.2	4711.4	3861.66			
		13508.6	14895.75	10.3%		383402.95

Table 4.46 Annual cost comparison between original and retrofit network for light crude

Cost ($/yr)	Existing	Retrofit
Total utility cost	7194849.7	5134137.63
Total fixed and area cost		383393.18
Total cost	7194849.7	5517530.80
Cost saving		1677318.93
(%)		23.31%

Retrofit with relocation of existing network is done. the operating cost is reduced from 7,194,709.4 $/yr to 5,133,997.37$/yr by switching position of heat exchanger net work before adding some area in existing area and with out adding any new heat exchanger in the existing HEN. The capital cost is 383393.18 $/yr. Total cost of retrofit with relocation of HEN was lower than total cost of retrofit without relocation. It results from switching position of heat exchanger network before adding area or adding new HEX.

4.4 Find the Best Network (one crude unit) for Handling Many Types of Crude by Grassroots Design

There are three types of crude; light, intermediate and heavy crude Refinery and their HENs are designed by grassroots design GAMS model as shown in Figure 4.16, 4.17 and 4.18.

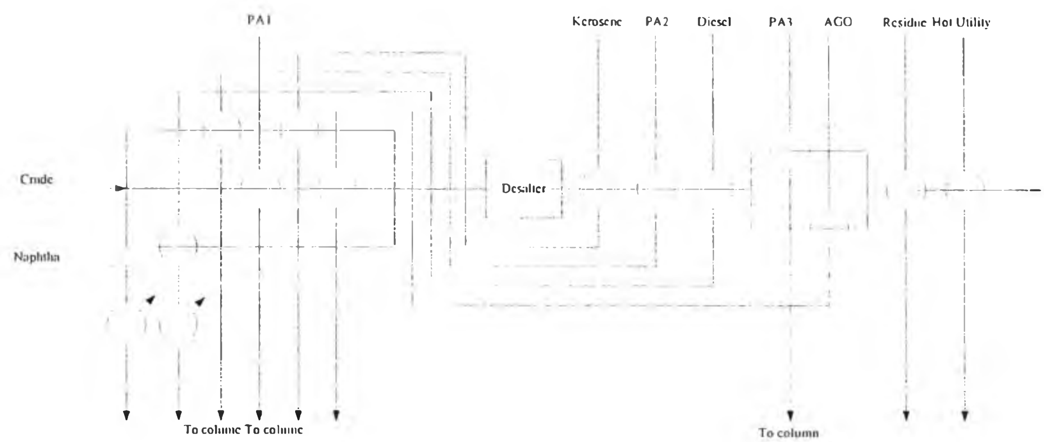

Figure 4.16 HEN1 design for light crude data by using GAMS

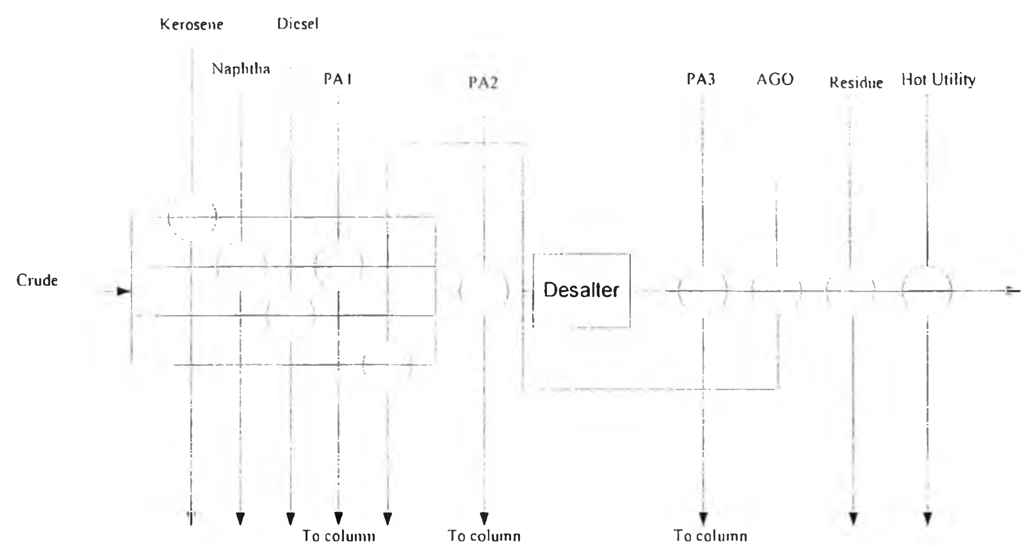

Figure 4.17 HEN2 design for intermediate crude data by using GAMS

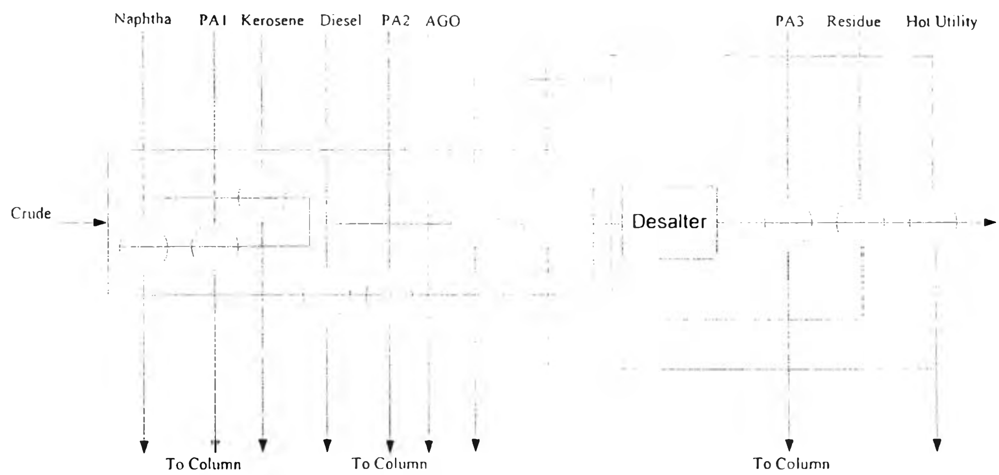

Figure 4.18 HEN3 design for heavy crude data by using GAMS

All heat exchanger networks, HEN1, HEN2 and HEN3 were run with all crude by using Pro II to find energy consumption shown in Table 4.47.

Table 4.47 Energy consumption of each HEN with all types of crudes

				QH (MJ/h)	QC (MJ/h)	Total	Total/HEN
Light Crude	HEN1	HEN1	Light	289733	13115.5	302848.5	
		HEN1	Intermediate	318117.2	9395.4	327512.6	
		HEN1	Heavy	347531.9	4686.5	352218.4	982579.5
Intermediate Crude	HEN2	HEN2	Light	335537.4	-	335537.4	
		HEN2	Intermediate	308460	-	308460	
		HEN2	Heavy	348295.9	-	348295.9	992293.3
Heavy Crude	HEN3	HEN3	Light	382381	-	382381	
		HEN3	Intermediate	350872.1	-	350872.1	
		HEN3	Heavy	339965.2	-	339965.2	1073218

HEN1 design for light crude consumes less utility than the others. HEN1 was the most suitable heat exchanger networks for every type of crude.

4.4.1 Scenario 1 the feed time ratio (Light: Intermediate: Heavy) of (3:3:4)

The results of scenario 1 are shown in Table 4.48

Table 4.48 Energy consumption of each HEN with all types of crude under scenario1

				Total	3:3:4		Total
Light Crude	HEN1	HEN1	Light	302848.5	3	90854.55	
		HEN1	Intermediate	327512.6	3	98253.78	
		HEN1	Heavy	352218.4	4	140887.4	329995.7
Intermediate Crude	HEN2	HEN2	Light	335537.4	3	100661.2	
		HEN2	Intermediate	308460	3	92538	
		HEN2	Heavy	348295.9	4	139318.4	332517.6
Heavy Crude	HEN3	HEN3	Light	382381	3	114714.3	
		HEN3	Intermediate	350872.1	3	105261.6	
		HEN3	Heavy	339965.2	4	135986.1	355962

HEN1 design from light crude consumes less utility than the others under the feed time ratio of 3:3:4 of light intermediate and heavy crude. HEN1 was the best heat exchanger networks for every type of crude.

4.4.2 Scenario 2 the feed time ratio (Light: Intermediate: Heavy) of (1:8:1)

The results of scenario 2 are shown in Table 4.49

Table 4.49 Energy consumption of each HEN with all types of crude under scenario2

				Total	10:80:10		Total
Light Crude	HEN1	HEN1	Light	302848.5	1	30284.85	
		HEN1	Intermediate	327512.6	8	262010.1	
		HEN1	Heavy	352218.4	1	35221.84	327516.8
Intermediate Crude	HEN2	HEN2	Light	335537.4	1	33553.74	
		HEN2	Intermediate	308460	8	246768	
		HEN2	Heavy	348295.9	1	34829.59	315151.3
Heavy Crude	HEN3	HEN3	Light	382381	1	38238.1	
		HEN3	Intermediate	350872.1	8	280697.7	
		HEN3	Heavy	339965.2	1	33996.52	352932.3

HEN2 design from intermediate crude consumes less utility than the others under the feed time ratio of 1:8:1 of light intermediate and heavy crude. HEN2 was the best heat exchanger networks for every type of crude.

4.4.3 <u>Scenario 3 the feed time ratio (Light: Intermediate: Heavy) of (0.5:0.5:9)</u>

The results of scenario 3 are shown in Table 4.50

Table 4.50 Energy consumption of each HEN with all types of crude under scenario3

				Total	05:05:90		Total
Light Crude		HEN1	Light	302848.5	0.5	15142.43	
		HEN1	Intermediate	327512.6	0.5	16375.63	
	HEN1	HEN1	Heavy	352218.4	9	316996.6	348514.6
Intermediate Crude		HEN2	Light	335537.4	0.5	16776.87	
		HEN2	Intermediate	308460	0.5	15423	
	HEN2	HEN2	Heavy	348295.9	9	313466.3	345666.2
Heavy Crude		HEN3	Light	382381	0.5	19119.05	
		HEN3	Intermediate	350872.1	0.5	17543.61	
	HEN3	HEN3	Heavy	339965.2	9	305968.7	342631.3

HEN3 design from intermediate crude consumes less utility than the others under the feed time ratio of 0.5:0.5:9 of light intermediate and heavy crude. HEN3 was the best heat exchanger networks for every type of crude.

4.5 Find the Best Network (one crude unit) for Handling Many Types of Crude by Retrofitting Network HEN1 (without relocation)

In this case HEN1 from 4.4 was modified to be the existing network (HEN0) for light, intermediate and heavy crude as shown in Figure 4.19. Here are three retrofit heat exchanger networks by GAMS model: HEN1.1, HEN 1.2 and HEN 1.3 as shown in Figure 4.19, 4.20 and 4.21.

Figure 4.19 HEN 0 existing HEN

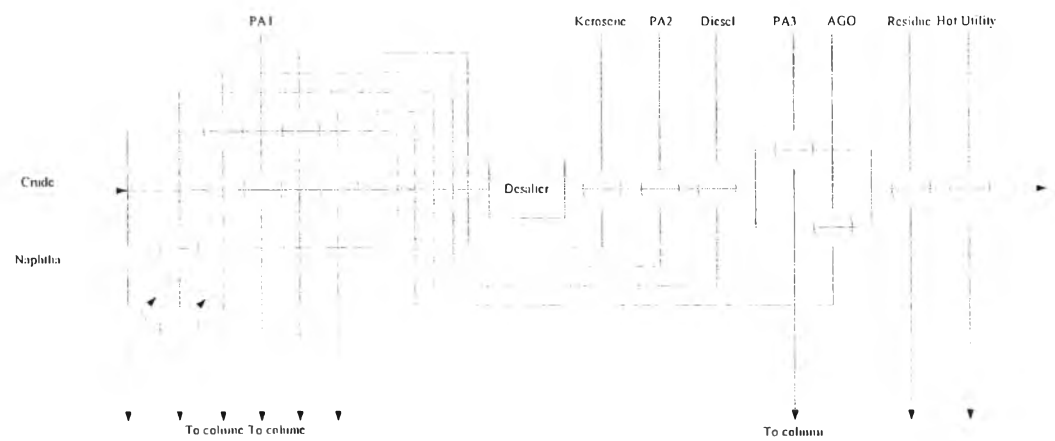

Figure 4.20 HEN1.1 Retrofit design for light crude

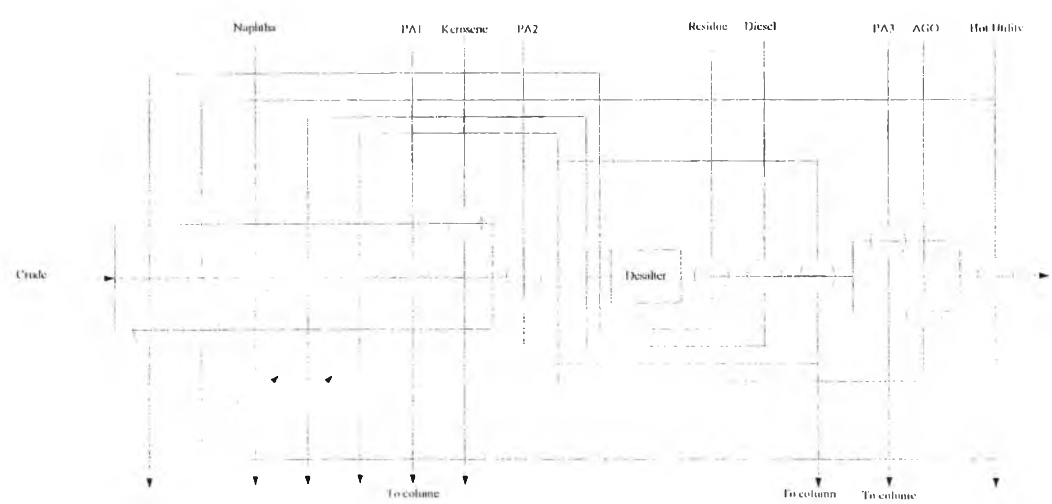

Figure 4.21 HEN1.2 Retrofit design for intermediate crude

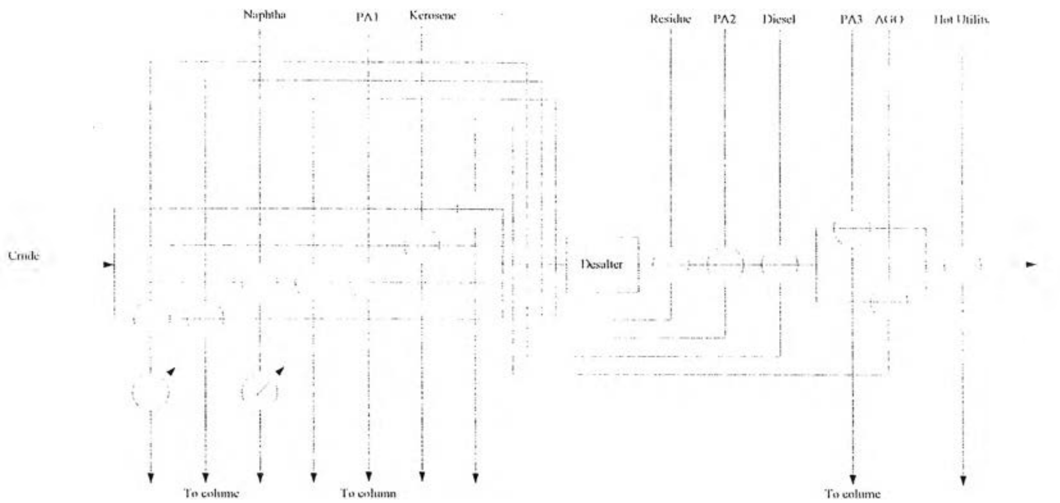

Figure 4.22 HEN1.3 Retrofit design for heavy crude

Total utilities of existing network (HEN0) is shown in Table 4.51

Table 4.51 Total utilities of existing network (HEN0)

		QH (MJ/h)	QC(MJ/h)	Total
HEN0	Light	310925	48509	359434
HEN0	Intermediate	321750	24158	345908
HEN0	Heavy	356837	33614	390451

All heat exchanger networks were run with all crude by using Pro II to find energy consumption from each couple which shown in Table 4.52.

Table 4.52 Energy consumption when match each HEN with all types of crude

			QH (MJ/h)	QC (MJ/h)	%Energy saving	%Energy saving of HEN
HEN1.1	HEN1.1	Light	289733	13115.5	15.74	5.61
	HEN1.1	Intermediate	318117.2	9395.4	8.88	
	HEN1.1	Heavy	382756.5	4686.5	-7.79	
HEN1.2	HEN1.2	Light	332994.3	9481.09	0.99	12.55
	HEN1.2	Intermediate	214071.8	3369.3	37.14	
	HEN1.2	Heavy	345448.2	2171.9	-0.49	
HEN1.3	HEN1.3	Light	351408.4	10909.4	7.21	12.47
	HEN1.3	Intermediate	322879.1	7891	15.29	
	HEN1.3	Heavy	327593.7	4611.8	14.92	

HEN1.2 design can save larger energy usage than the others. HEN1.2 was the most suitable heat exchanger networks for every type of crude.

There are three scenarios which were set to find opportunity that HEN1.1, HEN1.2 and HEN 1.3 are the best network when the uncertainty is considered to find the best network. In this case the uncertainty is the feed time ratio of crude.

4.5.1 Scenario 1 the feed time ratio (Light: Intermediate: Heavy) of (3:4:3)

The results of scenario 1 are shown in Table 4.52. Total utilities of existing network (HEN0) is shown in Table 4.53

Table 4.53 Total utilities of existing network (HEN0)

		QH (MJ/h)	QC(MJ/h)	Total
HEN0	Light	310925	48509	359434
HEN0	Intermediate	321750	24158	345908
HEN0	Heavy	356837	33614	390451

Table 4.54 Energy consumption of each HEN with all types of crude under scenario1

			QH (MJ/h)	QC (MJ/h)	% Energy Saving	(3:4:3)	% Energy Saving of HEN
	HEN1.1	Light	289733	13115.5	15.74	47.22884	
	HEN1.1	Intermediate	318117.2	9395.4	8.88	35.52407	5.94
HEN1.1	HEN1.1	Heavy	382756.5	4686.5	-7.79	-23.3776	
	HEN1.2	Light	332994.3	9481.09	0.99	2.977121	
	HEN1.2	Intermediate	214071.8	3369.3	37.13	148.5561	15
HEN1.2	HEN1.2	Heavy	345448.2	2171.9	-0.49	-1.48487	
	HEN1.3	Light	351408.4	10909.4	7.2	21.61593	
	HEN1.3	Intermediate	322879.1	7891	15.28	61.14048	12.75
HEN1.3	HEN1.3	Heavy	327593.7	4611.8	14.91	44.75248	

HEN1.2 design can save larger energy usage than the others under the feed time ratio of 3:4:3 of light intermediate and heavy crude. HEN1.2 was the best heat exchanger networks for every type of crude.

4.5.2 Scenario 2 the feed time ratio (Light: Intermediate: Heavy) of (8:1:1)

The results of scenario 2 are shown in Table 4.53. Total utilities of existing network (HEN0) is shown in Table 4.55

Table 4.55 Total utilities of existing network (HEN0)

		QH (MJ/h)	QC(MJ/h)	Total
HEN0	Light	310925	48509	359434
HEN0	Intermediate	321750	24158	345908
HEN0	Heavy	356837	33614	390451

Table 4.56 Energy consumption of each HEN with all types of crude under scenario2

			QH (MJ/h)	QC (MJ/h)	% Energy Saving	(8:1:1)	% Energy Saving of HEN
HEN1.1	HEN1.1	Light	289733	13115.5	15.74	125.9436	12.70
	HEN1.1	Intermediate	318117.2	9395.4	8.88	8.881018	
	HEN1.1	Heavy	382756.5	4686.5	-7.79	-7.79253	
HEN1.2	HEN1.2	Light	332994.3	9481.09	0.994	7.93899	4.46
	HEN1.2	Intermediate	214071.8	3369.3	37.13	37.13904	
	HEN1.2	Heavy	345448.2	2171.9	-0.49	-0.49496	
HEN1.3	HEN1.3	Light	351408.4	10909.4	7.20	57.64247	8.78
	HEN1.3	Intermediate	322879.1	7891	15.28	15.28512	
	HEN1.3	Heavy	327593.7	4611.8	14.91	14.91749	

HEN1.1 design can save larger energy usage than the others under the feed time ratio of 8:1:1 of light intermediate and heavy crude. HEN1.1 was the best heat exchanger networks for every type of crude.

4.5.3 Scenario 3 the feed time ratio (Light: Intermediate: Heavy) of (0.5:0.5:9)

The results of scenario 3 are shown in Table 4.54. Total utilities of existing network (HEN0) is shown in Table 4.57

Table 4.57 Total utilities of existing network (HEN0)

		QH (MJ/h)	QC(MJ/h)	Total
HEN0	Light	310925	48509	359434
HEN0	Intermediate	321750	24158	345908
HEN0	Heavy	356837	33614	390451

Table 4.58 Energy consumption of each HEN with **all** types of crude under scenario3

			QH (MJ/h)	QC (MJ/h)	% Energy Saving	(0.5:0.5:9)	% Energy Saving of HEN
HEN1.1	HEN1.1	Light	289733	13115.5	15.74	7.871473	-5.78
	HEN1.1	Intermediate	318117.2	9395.4	8.88	4.440509	
	HEN1.1	Heavy	382756.5	4686.5	-7.79	-70.1328	
HEN1.2	HEN1.2	Light	332994.3	9481.09	0.99	0.496187	1.46
	HEN1.2	Intermediate	214071.8	3369.3	37.13	18.56952	
	HEN1.2	Heavy	345448.2	2171.9	-0.49	-4.45462	
HEN1.3	HEN1.3	Light	351408.4	10909.4	7.20	3.602654	14.55
	HEN1.3	Intermediate	322879.1	7891	15.28	7.64256	
	HEN1.3	Heavy	327593.7	4611.8	14.91	134.2574	

HEN1.3 design can save larger energy usage than the others under the feed time ratio of 0.5:0.5:9 of light intermediate and heavy crude. HEN1.3 was the best heat exchanger networks for every type of crude.