CHAPTER IV

RESULTS AND DISCUSSION

There are many examples presented here to express the optimal heat exchanger network structure with minimum total cost. The case study from previous study of Barbaro A. and Vipanurat N., are also tested with the update mixed integer linear programming (MILP). The MILP model was constructed in GAMS and run in a PC with a 2.4 GHz processor and 1 Gb of RAM memory.

4.1 Grass-roots Design for HEN

4.1.1 Case study 4.1 (Problem 4.1 from Vipanurat's work)

This case study consists of two hot and two cold process streams, one hot and cold utility streams. The table below shows the details of hot (I) and cold (J) streams of case study 4.1

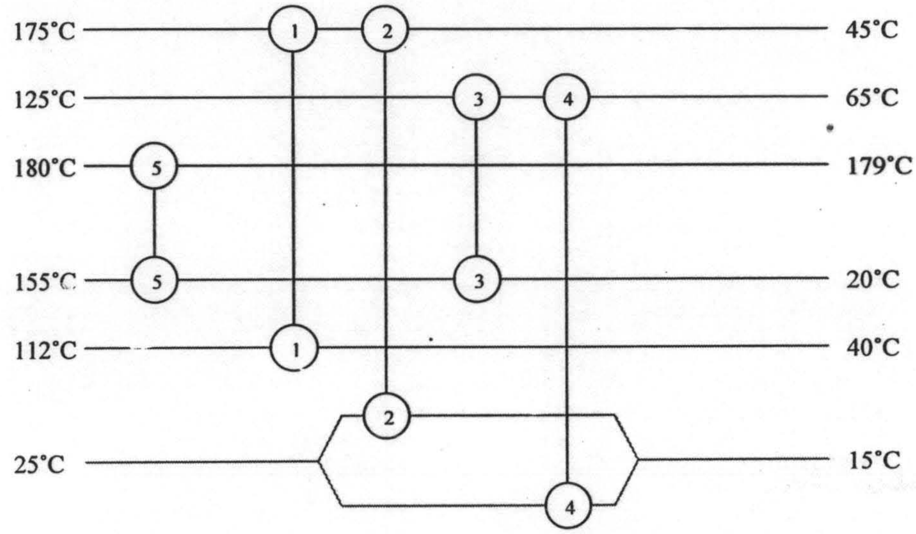
Table 4.1 Properties of stream for case study 4.1

Stream	F Ton/hr	Cp kJ/kg-C	Tin C	Tout C	h MJ/h-m²-C	Q MJ/hr
I1	10	1	175	45	0.2	1300
I2	40	1	125	65	0.2	2400
I3		1	180	179	0.2	
J1	20	1	20	155	0.2	2700
J2	15	1	40	112	0.2	1080
J3		1	15	25	0.2	

Table 4.2 Cost data for case study 4.1

Utilities	Cost \$/(MJ/hr-yr)
I3	19.75
J3	1.861
Heat Exchanger Cost 5291.9+77.788 A \$/yr	

Following model testing condition is the minimum approach temperature of 20 °C and the temperature intervals of 26 with one heat transfer zones, the result of heat exchanger network are shown in Figure 4.1. This heat exchanger network consumes 1157.143 MJ/hr of hot utility and 107.714 MJ/hr of cold utility with $136052.54 as the total cost.



No.of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1542.86	857.143	1157.14
Area (m²)	292.109	56.101	347.833	155.691	237.572

Figure 4.1 Heat exchanger network for case study 4.1 at 26 intervals.

Additionally, the effect of number of temperature intervals in each process streams on the total cost of HENs need to be studied. Following the process streams property in the case study 4.1, increasing the number of temperature intervals is simulated and the result is shown in Table 4.3

Table 4.3 Result of increasing number of intervals in case study 4.1

No. of interval	Total cost $/yr	Total Area m²	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed cost $/yr	Area cost $/yr	Utility cost $/yr
26	136052.5	1089.306	1157.143	1077.14	2234.283	26459.5	84734.94	24858.13
56	133862.8	1066.297	1138.636	1058.64	2197.276	26459.5	82945.11	24458.19
112	133808.5	1061.831	1152.198	1072.20	2224.398	26459.5	82597.71	24751.27
160	133731.8	1047.565	1200.000	1120.00	2320.000	26459.5	81487.99	25784.32

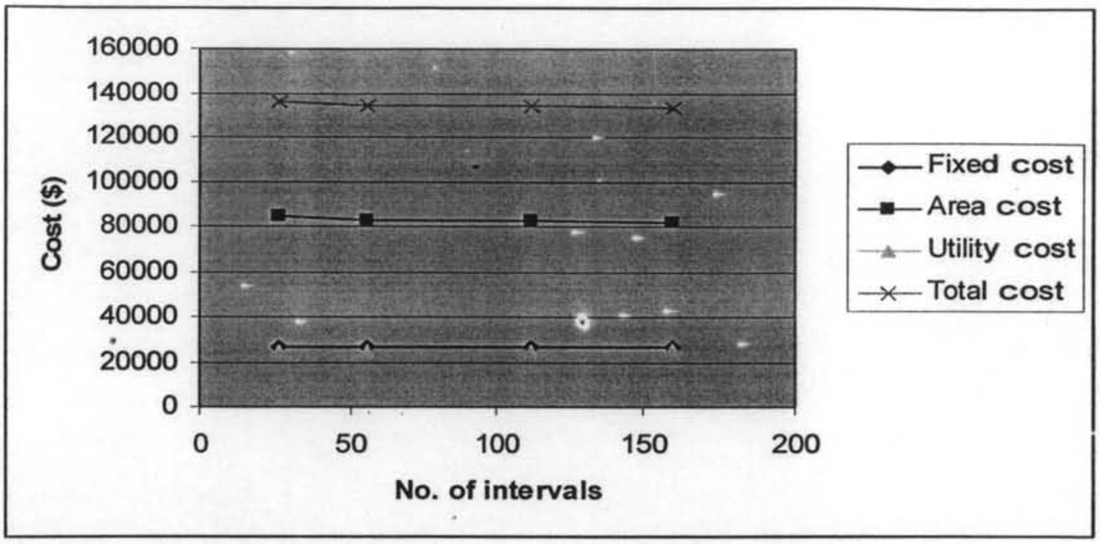
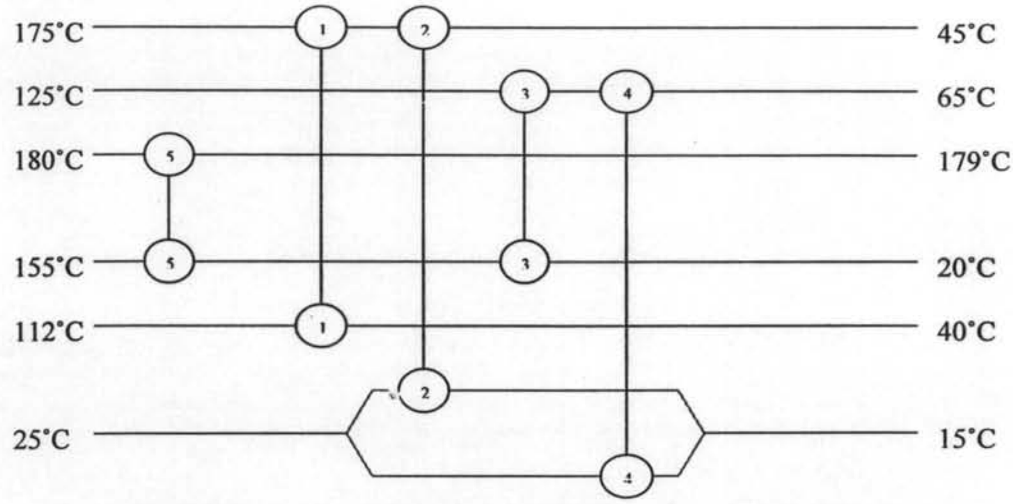


Figure 4.2 Trend of varying the intervals for case study 4.1.

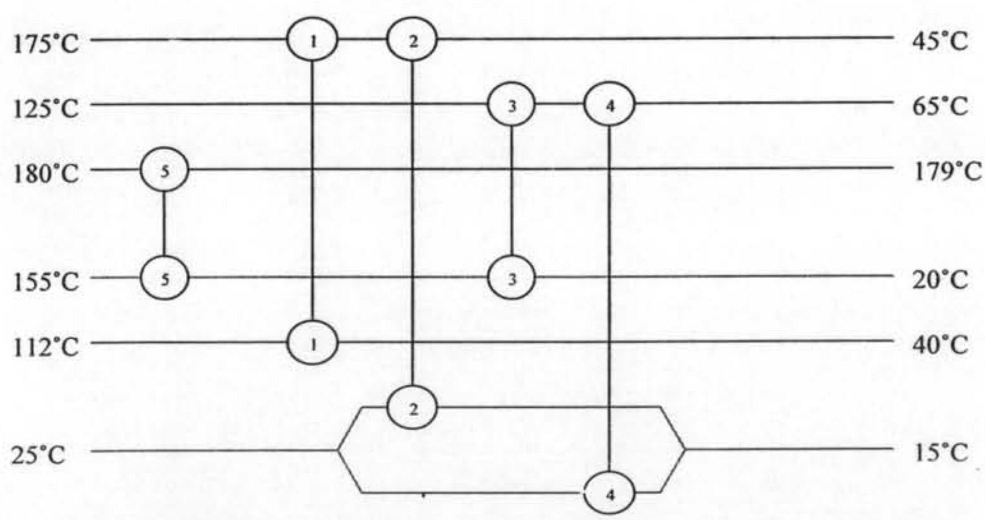
The result of objective function including the cost of the utility, fixed and area costs, heat exchanger area, and the total energy usage. Figure 4.2 shows the trend of all these values with various number of temperature intervals. All the intervals give the same number of heat exchanger so the fixed cost is constant in all of intervals. The trend of utility cost is increased following the increase of intervals except the area cost. The heat exchanger network of the other intervals are shown in Figure 4.3

(a) 56 intervals



No.of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1561.36	838.636	1138.64
Area (m^2)	256.426	61.526	359.216	151.47	237.659

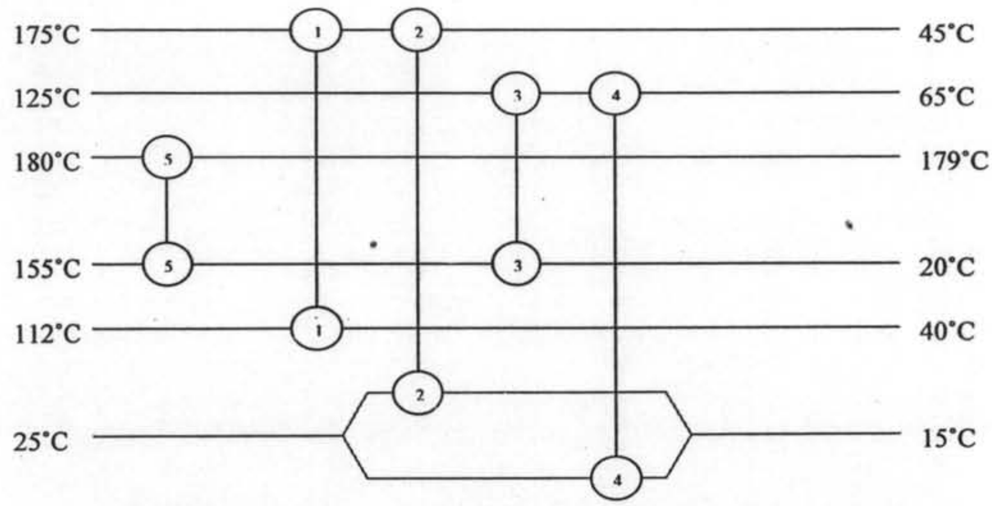
(b) 112 intervals



No.of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1547.8	852.198	1152.2
Area (m^2)	254.903	61.628	351.257	153.58	240.463

Figure 4.3 Heat exchanger network for case study 4.1.

(C) 160 intervals



No.of heat exchanger	1	2	3	4	5
Heat Load (MJ/hr)	1080	220	1500	900	1200
Area (m²)	254.582	61.64	324.32	160.68	246.343

Figure 4.3 (Cont.) Heat exchanger network for case study 4.1.

4.1.2 Case study 4.2 (Problem 4.2 from Vipanurat's work)

In this case study, There are six hot process streams (I1-I6), one cold stream (J1), one heating utility (I7) and one cooling utility (J2). The table below shows the details of each streams of case study 4.2

Table 4.4 Properties of stream for case study 4.2

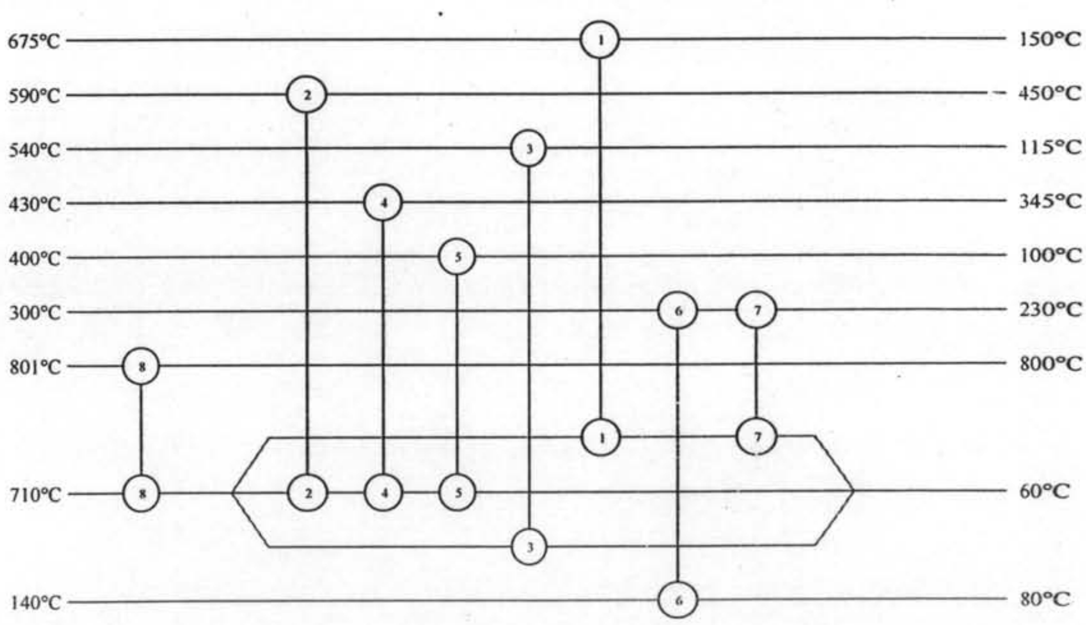
Stream	F Ton/hr	Cp kJ/kg-C	Tin C	Tout C	h MJ/h-m²-C	Q MJ/hr
I1	15	1	675	150	0.2	7875
I2	11	1	590	450	0.2	1540
I3	4.5	1	540	115	0.2	1912.5
I4	60	1	430	345	0.2	5100
I5	12	1	400	100	0.2	3600
I6	125	1	300	230	0.2	8750
I7		1	801	800	0.2	
J1	47	1	60	710	0.2	30550
J2	110.3	1				

Table 4.5 Cost data for case study 4.2

Utilities	Cost $/(MJ/hr-yr)
I7	19.75
J2	1.861
Heat Exchanger Cost 5291.9+77.788 A $/yr	

The result structures simulated by MILP model are drawn in Figure 4.4. The network configurations are consisted of eight exchangers units in the structure at 58 intervals but the structure at 72, 116 and 125 intervals have nine exchangers. Table 4.6 shows the result of case study 4.2 in each temperature intervals.

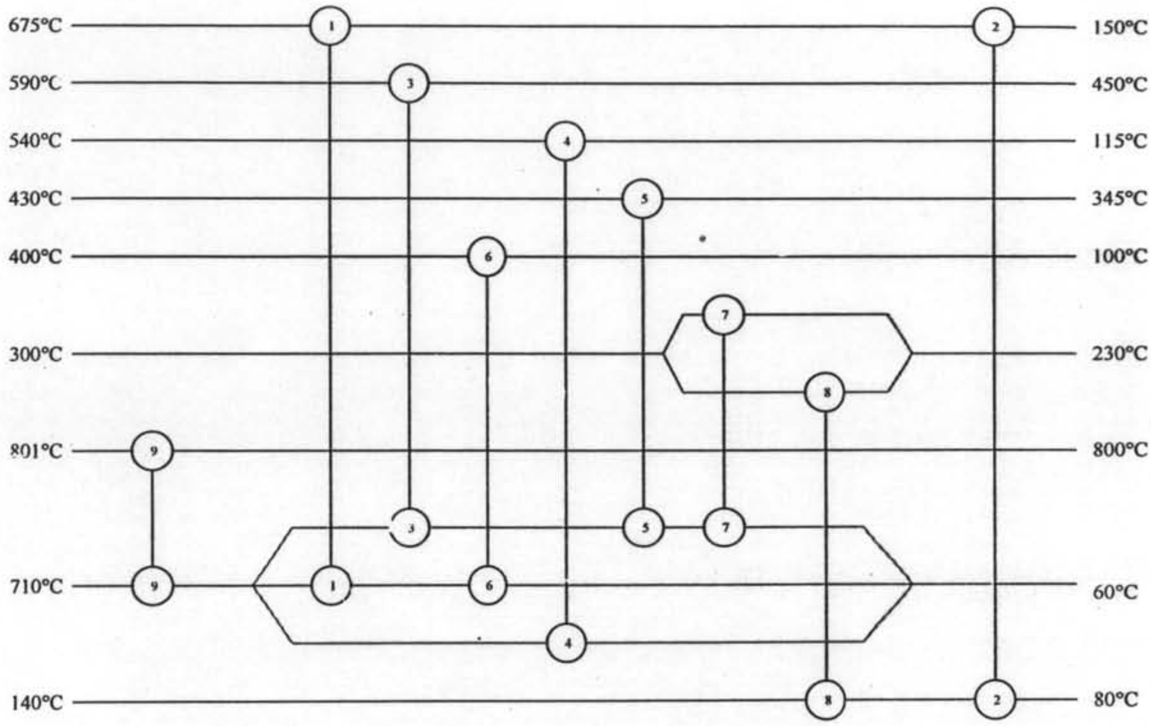
(a) 58 intervals



No.of heat exchanger	1	2	3	4	5	6	7	8
Heat Load (MJ/hr)	7875	1540	1912	5100	3600	1514.793	7235.21	11827.71
Area (m^2)	626.214	143.331	175.569	484.785	239.565	75.19	451.644	616.733

Figure 4.4 Heat exchanger network for case study 4.2.

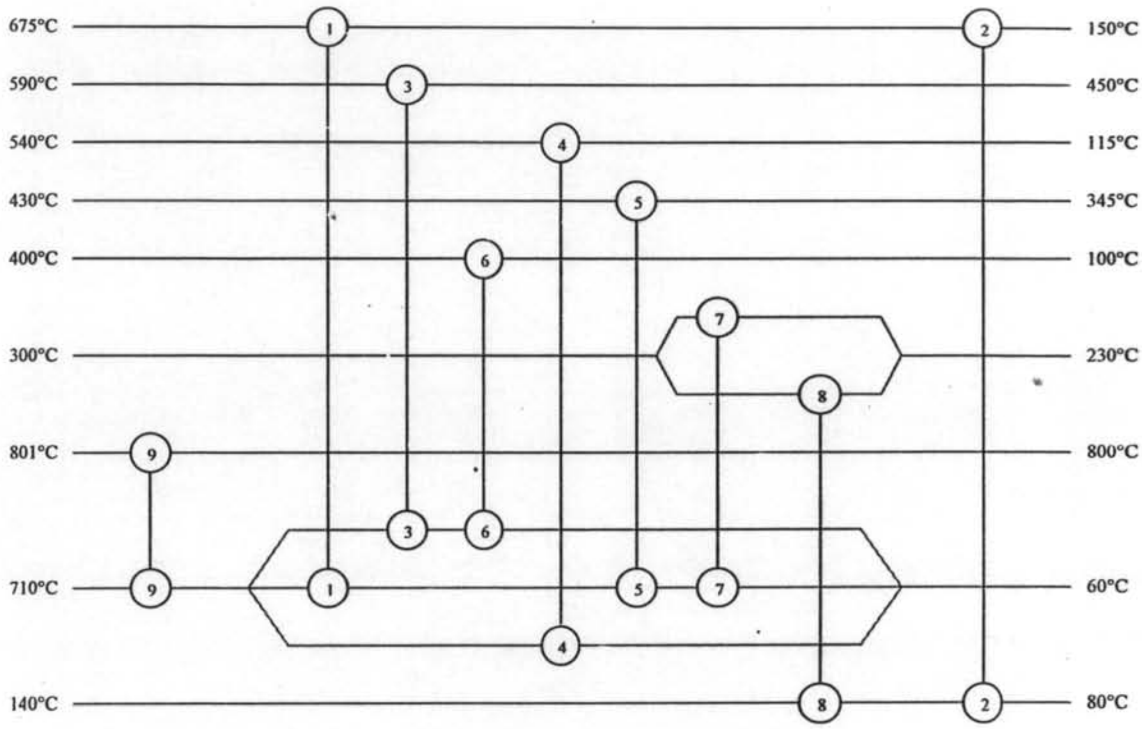
(b) 72 intervals



No.of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4754.67	3120.33	1540	1912.5	5100	3600	5629.67	3120.33	10833.16
Area (m²)	496.774	223.942	164.68	165.751	473.219	346.899	347.19	225.193	589.754

Figure 4.4 (Cont.) Heat exchanger network for case study 4.2.

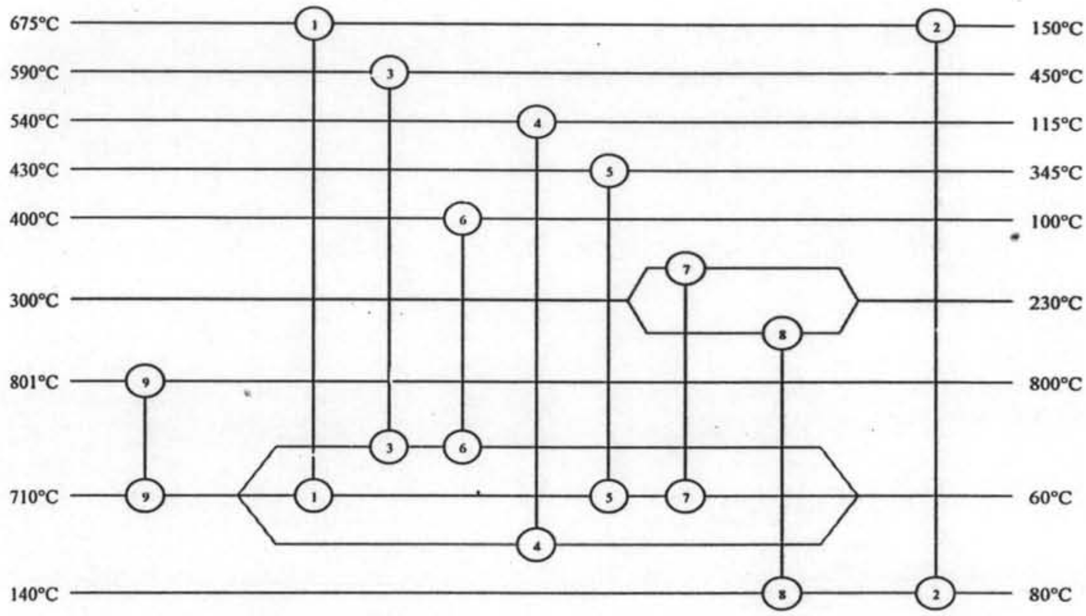
(c) 116 intervals



No.of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4559.21	3315.79	1540	1912.5	5100	3600	5304.85	3445.151	11353.44
Area (m^2)	428.058	229.489	132.747	180.542	435.853	266.513	343.803	247.397	607.533

Figure 4.4 (Cont.) Heat exchanger network for case study 4.2.

(d) 125 intervals



No.of heat exchanger	1	2	3	4	5	6	7	8	9
Heat Load (MJ/hr)	4331.25	3543.75	1540	1912.5	5100	3600	5675.75	3074.25	11210.5
Area (m^2)	387.142	238.041	135.856	192.384	468.835	271.95	387.087	222.728	603.175

Figure 4.4 (Cont.) Heat exchanger network for case study 4.2.

Table 4.6 shows the results simulated at one heat transfer zone operating. There is quite a few fluctuation of total cost by changing the number of temperature interval. HEN structures at 72, 116 and 125 intervals are almost similar. They have some different flow rate of hot and cold stream, but the matches of hot and cold streams are the same. Area and utility costs are the major reasons for total cost variation. In general, heat exchanger area is traded off with the amount of utility consumption. Small utility usage will cause larger exchanger area, because the larger heat exchange is required with less utility usage.

Table 4.6 Result of increasing number of intervals in case study 4.2

No. of interval	Total cost $/yr	Total Area m²	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed cost $/yr	Area cost $/yr	Utility cost $/yr
58	508217.1	2813.031	11827.7	7235.22	19062.927	42335.2	218820.0	247061.9
72	509158.1	3033.402	10833.1	6240.66	17073.819	47627.1	235962.2	225568.7
116	507841.8	2871.935	11353.4	6760.92	18114.361	47627.1	223402.0	236812.5
125	507495.6	2907.198	11210.5	6618.00	17828.500	47627.1	226145.1	233723.4

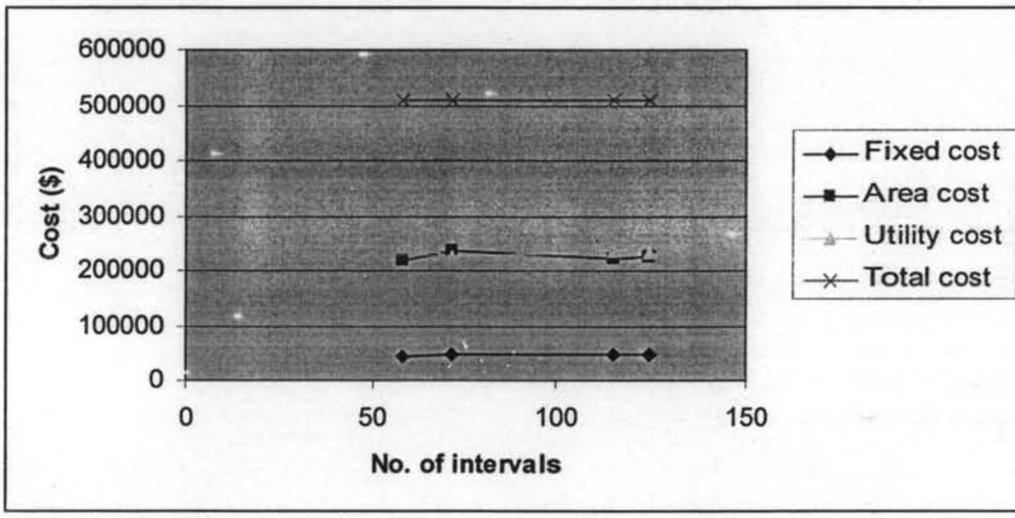


Figure 4.5 Trend of varying the intervals for case study 4.2.

4.1.3 <u>Case study 4.3 (Problem 4.4 from Vipanurat's work)</u>

There are three hot process streams (I1-I3), two cold streams (J1-J2), one heating utility (I4) and one cooling utility (J3). The Table 4.7 shows the details of hot (I) and cold (J) streams of case study 4.3. And Table 4.8 shows the cost of utility and heat exchanger.

Table 4.7 Properties of stream for case study 4.3

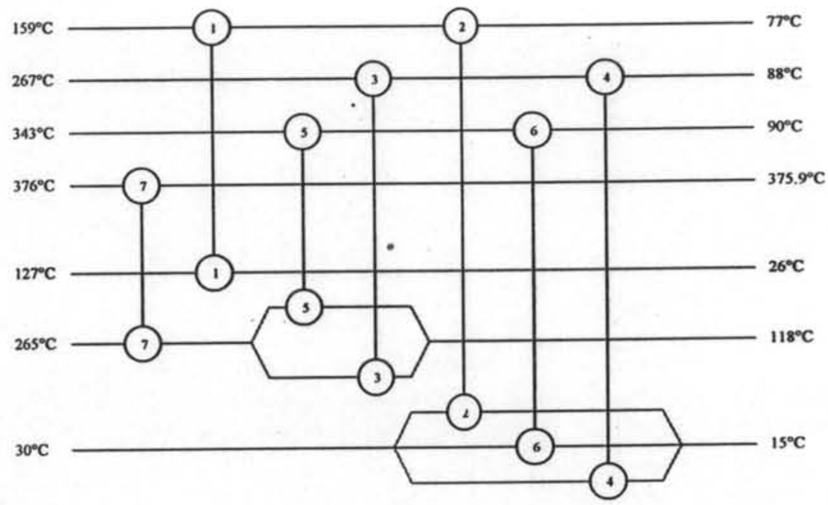
Stream	F Ton/hr	Cp kJ/kg-C	Tin C	Tout C	h MJ/h-m²-C	Q MJ/hr
I1	228.5	1	159	77	0.4	187.37
I2	20.4	1	267	88	0.3	3651.6
I3	53.8	1	343	90	0.25	13611.4
I4		1	376	375.9	1	
J1	93.3	1	26	127	0.15	9423.3
J2	196.1	1	118	265	0.5	28826.7
J3		1	15	30	0.6	

Table 4.8 Cost data for case study 4.3

Utilities	Cost $/(MJ/hr-yr)
I4	19.75
J3	1.861
Heat Exchanger Cost 8153.9+61.75 A $/yr	

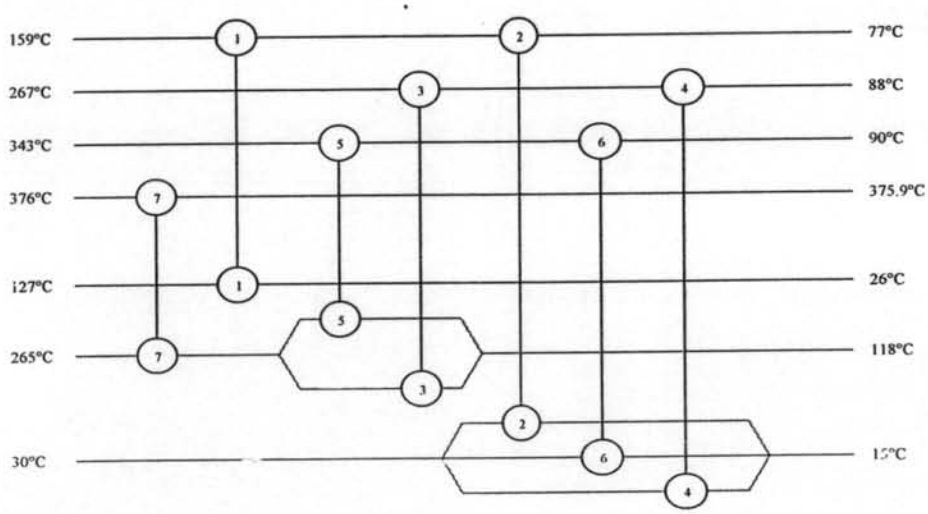
The result structures simulated by MILP model are drawn in Figure 4.6. The network configurations of all intervals are consisted of seven exchangers units which it have same the heat exchanger network. Table 4.7 shows the result of case study 4.3 in each temperature intervals.

(a) 67 intervals



No.of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	9423.3	9313.7	2434.4	1217.2	11018.8	2592.648	15373.5
Area (m^2)	1551.35	518.853	245.112	67.071	1029.47	164.421	313.957

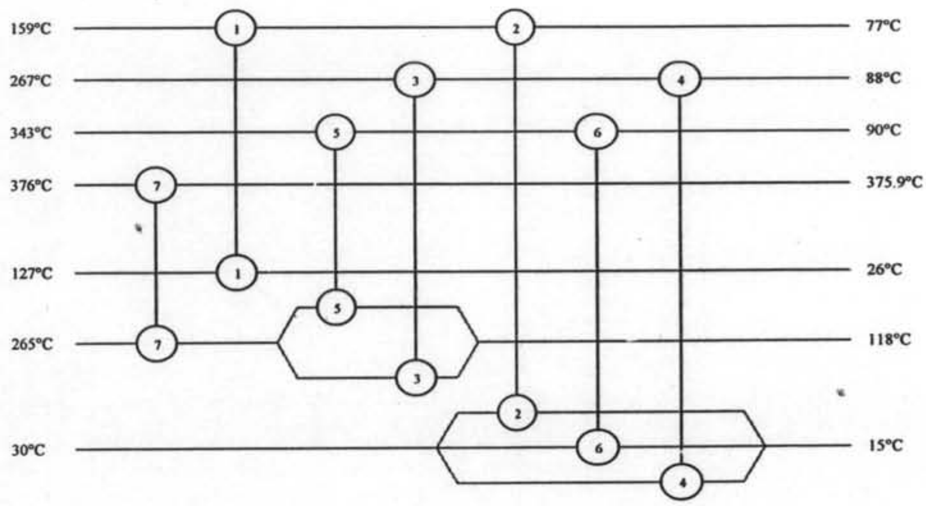
(b) 134 intervals



No.of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	9423.3	9313.7	2556.12	1095.48	11018.8	2592.648	15251.8
Area (m^2)	1529.28	523.829	292.583	60.249	1005.49	162.265	312.385

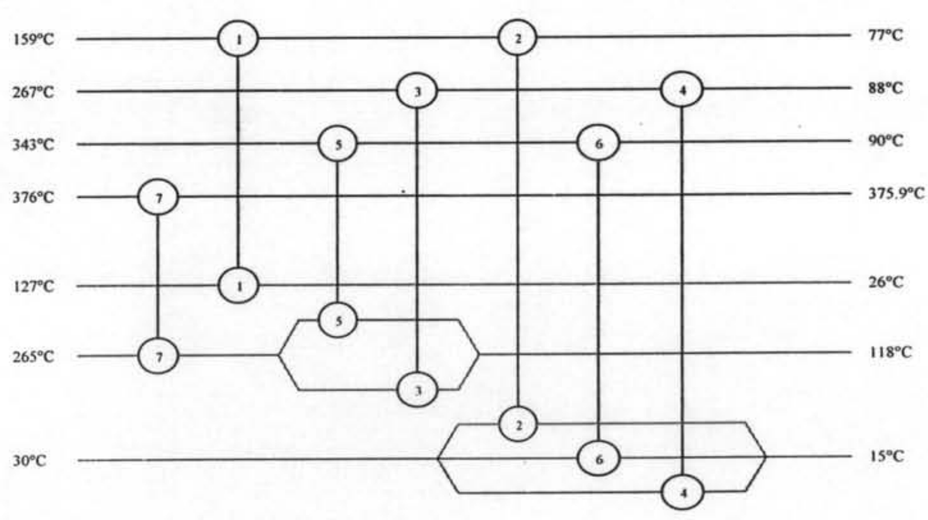
Figure 4.6 Heat exchanger network for case study 4.3.

(c) 165 intervals



No.of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	9423.3	9313.7	2577.6	1074	10948.3	2663.1	15300.8
Area (m^2)	1526.76	523.308	302.099	59.335	973.662	165.569	313.21

(d) 165 intervals



No.of heat exchanger	1	2	3	4	5	6	7
Heat Load (MJ/hr)	9423.3	9313.7	2582.84	1068.76	10993.8	2617.577	15280
Area (m^2)	1524.65	523.481	301.285	59.106	992.03	163.397	312.407

Figure 4.6 (Cont.) Heat exchanger network for case study 4.3.

Table 4.9 Result of increasing number of intervals in case study 4.3

No. of interval	Total cost $/yr	Total Area m²	Hot Utility MJ/hr	Cold Utility MJ/hr	Total Utility MJ/hr	Fixed cost $/yr	Area cost $/yr	Utility cost $/yr
67	625350.1	3890.238	15373.55	13123.55	28497.093	57077.3	240222.2	328050.5
134	622462.5	3886.076	15251.83	13001.84	28253.663	57077.3	239965.2	325420.0
165	622153.9	3863.940	15300.80	13050.80	28351.595	57077.3	238598.3	326478.3
207	621823.6	3876.355	15250.04	13000.04	28250.073	57077.3	239364.9	325381.3

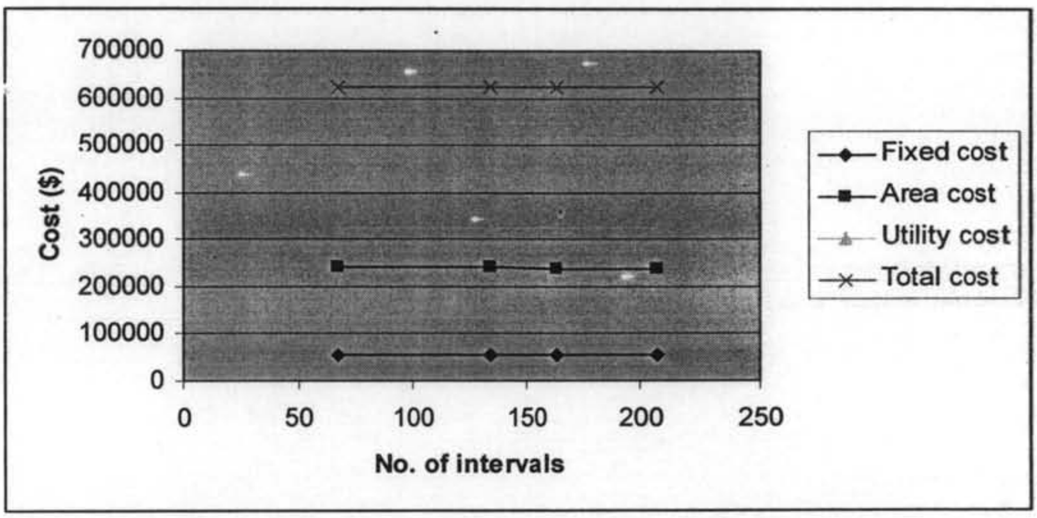


Figure 4.7 Trend of varying the intervals for case study 4.3.

In summary, the MILP model has an effective performance in term of the objective function stability and also generates the possible heat exchanger network design for heat exchanging process composed of various number of hot and cold process streams. According to network structure of all problems above, the total costs are eventually getting into stable even the number of temperature interval is increased. Moreover, heat exchanger network structures at any intervals of each problem are getting to be the same whereas the interval number is increased.

4.2 Retrofit for Heat Exchanger Networks

4.2.1 Case study 4.4 (Problem 4.5 from Vipanurat's work)

This case study consists of three hot and two cold process streams with one hot and one cold utility. The stream data properties and cost data are given in Table 4.9 and 4.10. The existing heat exchanger network configuration, Figure 4.8, consumes 17,597 kW of hot utility and 15,510 kW of cold utility. The retrofit result is shown in Figure 4.9. Three new exchanger units are installed, area of 403.672 m^2 is added to existing heat exchanger and 13651.020kW of hot utility and 11411.12kW of cold utility are required. The model can generate the retrofit network with total cost saving 10.57% or 209.5 k$/yr.

Table 4.10 Properties of stream for case study 4.4

Stream	F Ton/hr	Cp kJ/kg-K	Tin K	Tout K	h MJ/h-m²-K
I1	228.5	1	432	350	0.4
I2	20.4	1	540	361	0.3
I3	53.8	1	616	363	0.25
I4		1	773	772	0.53
J1	93.3	1	299	400	0.15
J2	196.1	1	391	538	0.5
J3		1	293	313	0.53

Table 4.11 Cost data for case study 4.4

Utilities	Cost $/(MJ/hr-yr)
I4	95.04
J3	20
Heat Exchanger Cost 3460+171.4 A $/yr	

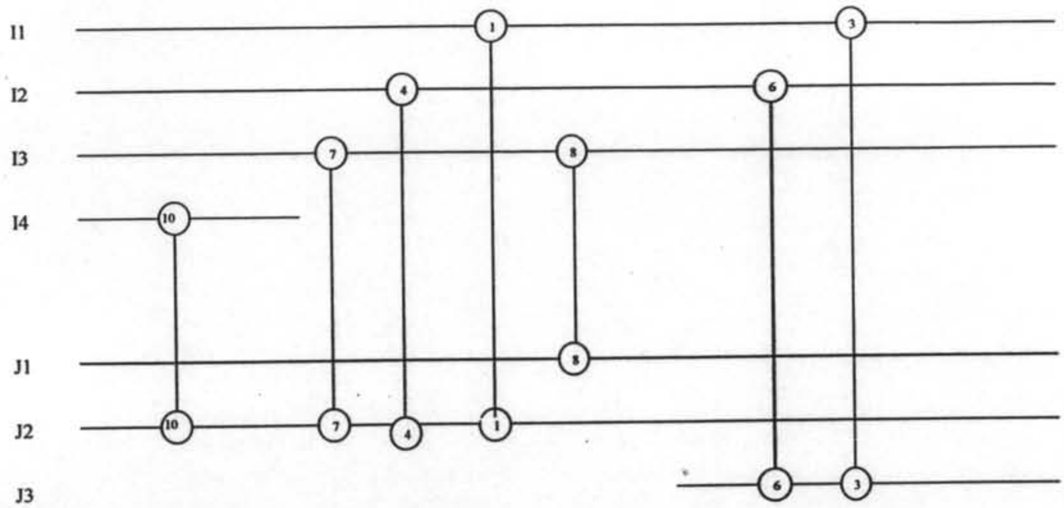


Figure 4.8 The existing heat exchanger network for case study 4.4.

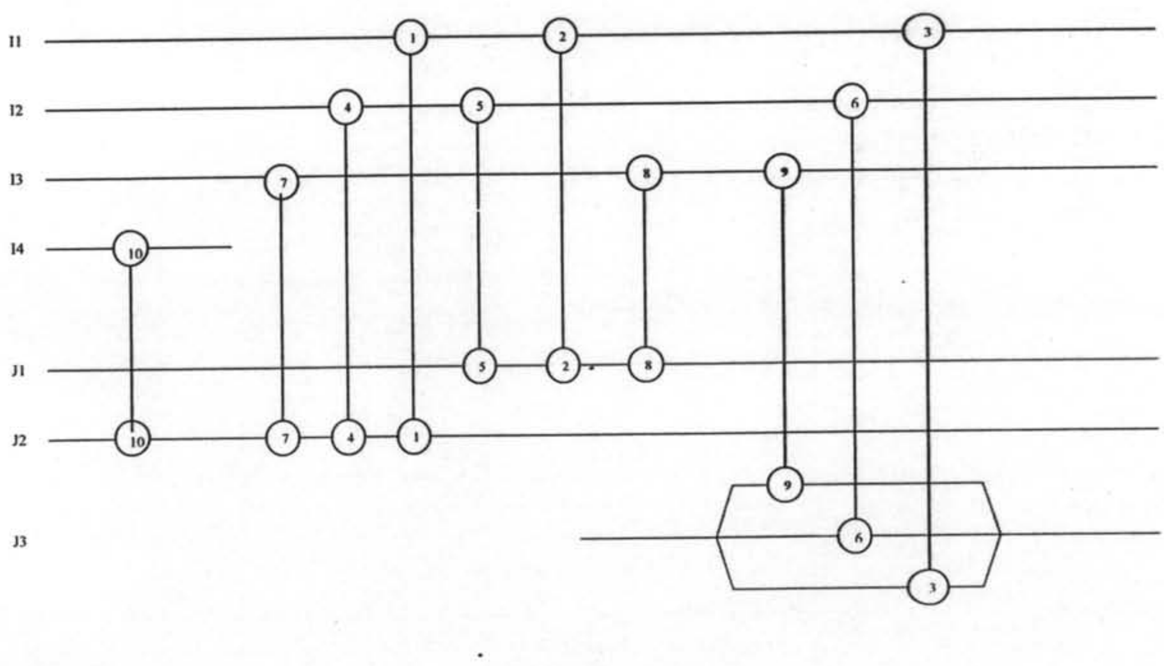


Figure 4.9 The retrofit heat exchanger network for case study 4.4.

Table 4.12 Resulting of retrofit heat exchanger for case study 4.4

HE	Retrofit load kW	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	Cost $
1	5494276	1001.34	1001.34			
2	3603.337		720.107		720.107	126886.3
3	9639.387	1048.28	654.538			
4	706.206		207.166		207.166	36968.25
5	1849.914	121.53	182.295	60.765		10415.12
6	1095.48	133.56	71.606			
7	3212.718	584.15	667.957	83.807		14364.52
8	9722.429	603.71	862.81	259.100		44409.74
9	676.253		51.97		51.970	12367.66
10	13651.02	246.81	197.804			
		3739.38	4617.593	23.49%		247411.6

Table 4.13 Annual cost comparison between original and retrofit network for case study 4.4

Cost ($/yr)	Existing	Retrofit
Total utility cost	1982618.88	1525615.496
Total fixed and area cost		247411.6
Total cost	1982618.88	1773027.096
Cost saving		209591.784
(%)		10.57%

4.2.2 Case study 4.5 (Problem 4.6 from Vipanurat's work)

Case study 4.5 is the retrofit problem of crude distillation unit composed of 17 streams and 17 existing exchangers. Streams properties are shown in Table 4.13 and Table 4.14. While the results of retrofit network are given in Table 4.15. Cost comparisons are given in Table 4.16.

The retrofit solution achieves 78.23% annual cost savings or 5.37 M$/yr with three new exchanger units and area 53.924m² is added into existing heat exchanger and three heat exchanger form existing network are removed. The original and retrofit networks arc shown in Figure 4.10 and 4.11.

Table 4.14 Properties of stream for case study 4.5

Stream	F Ton/hr	Cp kJ/kg-K	Tin K	Tout K	h MJ/h-m²-K
I1	155.1	3.161	319.4	244.1	4.653
I2	5.695	4.325	73.24	30	18.211
I3	251.2	3.111	347.3	202.7	3.21
		2.573	202.7	45	2.278
I4	151.2	2.93	263.5	180.2	4.894
I5	26.03	3.041	45	203.2	4.674
		2.689	203.2	110	3.952
I6	86.14	2.831	110	147.3	4.835
		2.442	147.3	50	3.8
I7	91.81	2.262	73.24	40	4.605
I8	63.99	2.854	50	176	5.023
		2.606	176	120	4.846
I9	239.1	2.595	167.1	116.1	4.995
		2.372	116.1	69.55	4.88
I10	133.8	6.074	146.7	126.7	1.807
		4.745	126.7	99.94	3.373
		9.464	99.94	73.24	6.878
I11			250	249	21.6
I12			1000	500	0.4
J1	519	2.314	30	108.1	1.858
		2.645	108.1	211.3	2.356
		3.34	211.3	232.2	2.212
J2	496.4	3.54	232.2	343.3	2.835
J3	96.87	13.076	226.2	228.7	11.971
		15.808	228.7	231.8	11.075
J4			20	25	13.5
J5			124	125	21.6
J6			174	175	21.6

Table 4.15 Cost data for case study 4.5

Utilities	Cost $/(MJ/hr-yr)
I11	19.75
I12	37.222
J4	1.861
J5	-6.494
J6	-12.747
Heat Exchanger Cost 5291.9+77.788 A $/yr	

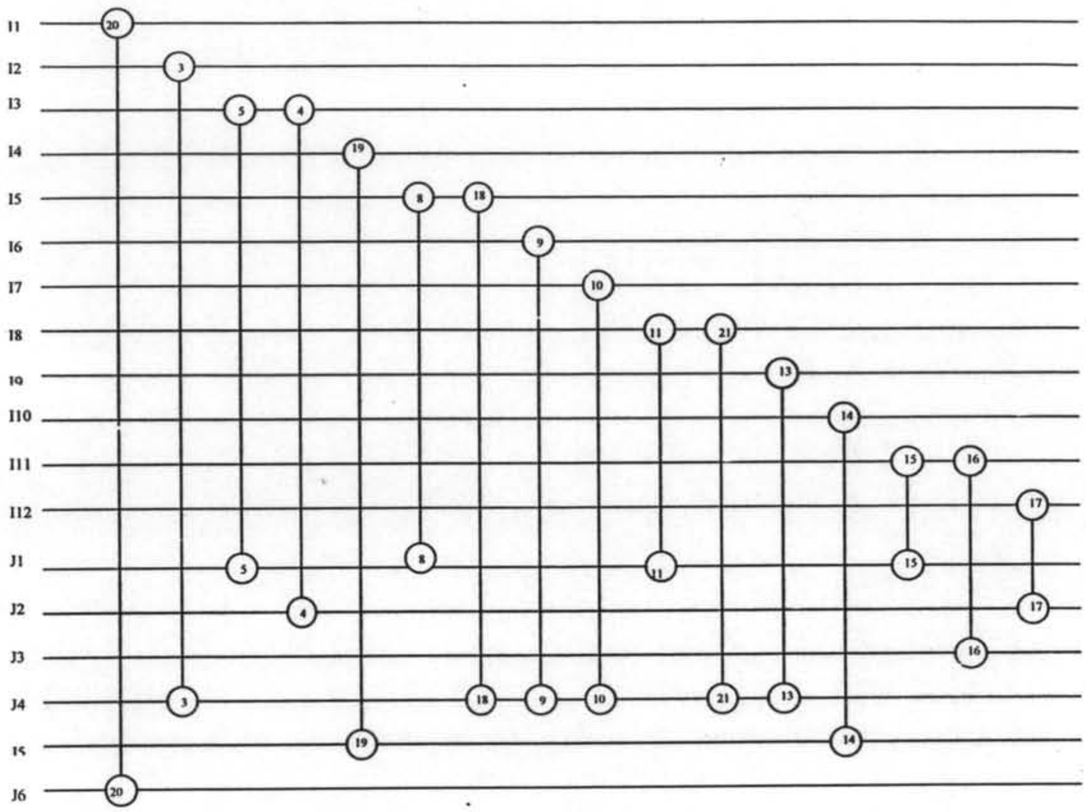


Figure 4.10 The existing heat exchange network for case study 4.5.

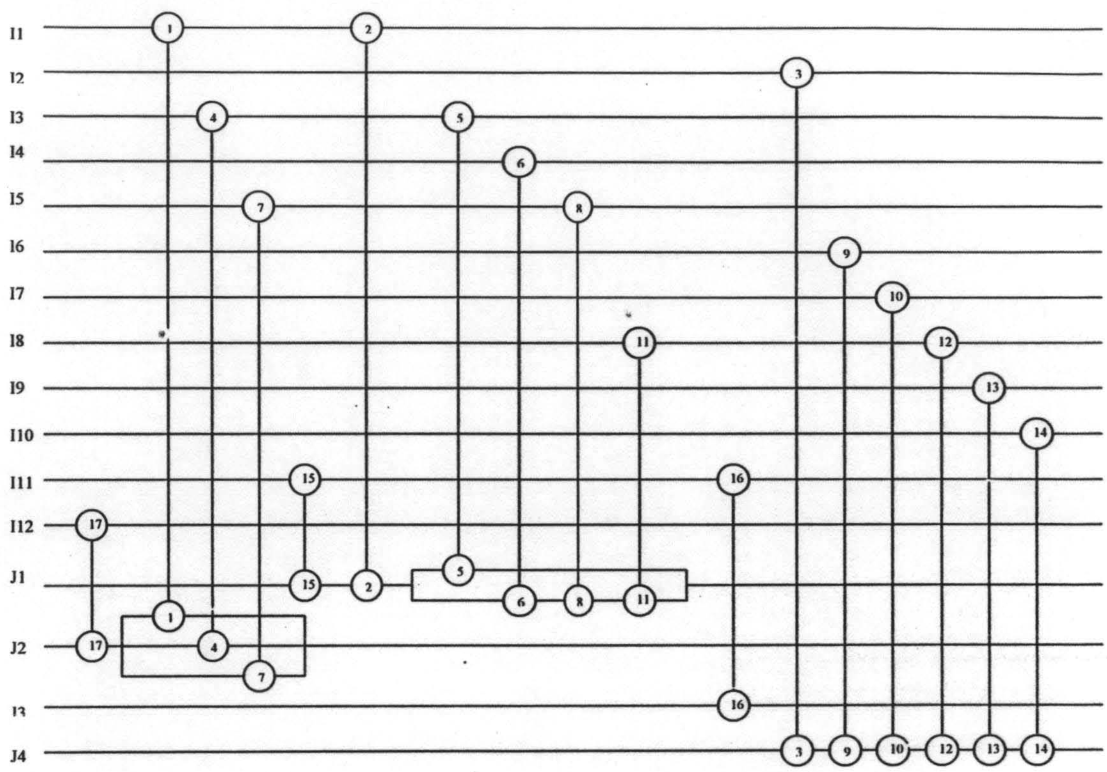


Figure 4.11 The retrofit heat exchange network for case study 4.5.

Table 4.16 Resulting of retrofit heat exchanger for case study 4.5

HE	Retrofit load kW	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	Cost $
1	1946.505		15.334		15.334	6484.701
2	9732.525		324.19		324.19	30509.99
3	246.252	5.5	1.357			
4	52768.811	4303.2	1825.232			
5	23168.949	685.7	703.764	18.064		1405.162
6	12594.96		92.785		92.785	12509.46
7	3624.181		31.703			
8	1253.841	93.7	93.7			
9	17055.72	145	57.724			
10	3051.764	59.4	28.204			
11	5169.427	24.6	27.06	2.46		191.3585
12	1984.655		4.907			2598.119
13	23324.205	183.3	74.195			
14	9828.948	278.1	43.919			
15	28837.916	1212.7	362.106			
16	542.472	53.5	3.552			
17	20994.725	976.4	159.045			
18		2.3				
19		101.6				
20		93.9				
21		33.4				
		8318.6	3848.777			53698.79

Table 4.17 Annual cost comparison between original and retrofit network for case study 4.5

Cost ($/yr)	Existing	Retrofit
Total utility cost	6865616.51	1441232.348
Total fixed and area cost		53698.79
Total cost	6865616.51	1494931.138
Cost saving		5370685.372
(%)		78.23%

4.2.3 Case study 4.6 (Problem 4.7 from Vipanurat's work)

In this case study, Table 4.17 shows the stream and cost data of crude distillation unit consisting of 12 streams and 11 existing units. Figure 4.12 shows the original network and Figure 4.13 shows the retrofit structure generated by our MILP strategy. The results are shown in Tables 4.19 and the total annual cost in Table 4.20. The retrofit has a 0.99% saving over the original structure. An area 47.718 m² is added into existing heat exchanger and three new heat exchangers are added into the network.

Table 4.18 Properties of stream for case study 4.6

Stream	FCp kW/C	Tin C	Tout C	h MJ/h-m²-C
I1	470	140	40	0.8
I2	825	160	120	0.8
I3	42.42	210	45	0.8
I4	100	260	60	0.8
I5	357.14	280	210	0.8
I6	50	350	170	0.8
I7	136.36	380	160	0.8
I8		500	499	0.8
J1	826.09	270	385	0.8
J2	500	130	270	0.8
J3	363.64	20	130	0.8
J4		20	40	0.8

Table 4.19 Cost data for case study 4.6

Utilities	Cost $/(MJ/hr-yr)
I8	60
J4	5
Heat Exchanger Cost 300 A $/yr	

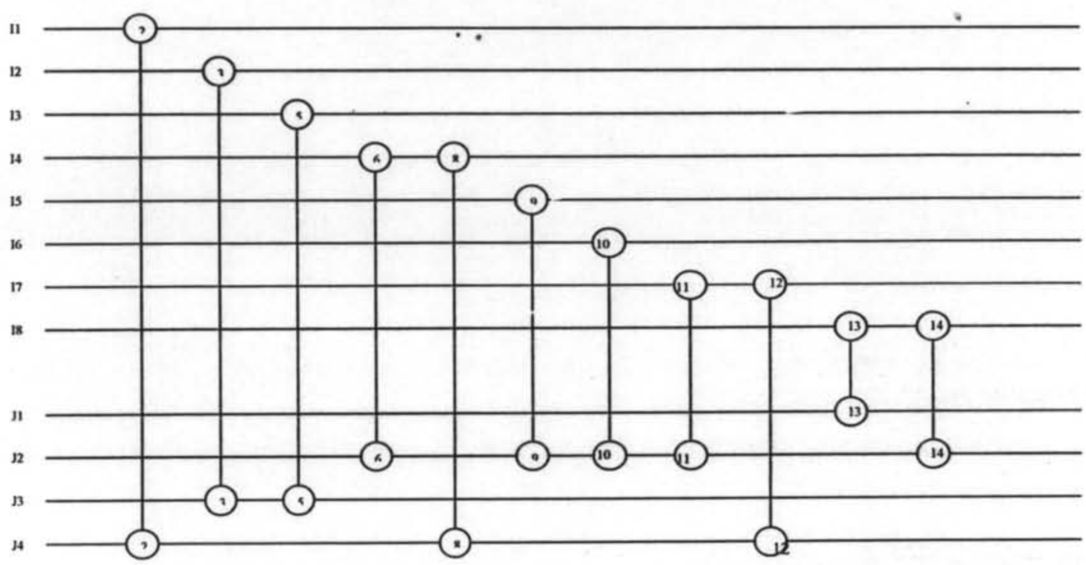


Figure 4.12 The existing heat exchange network for case study 4.6.

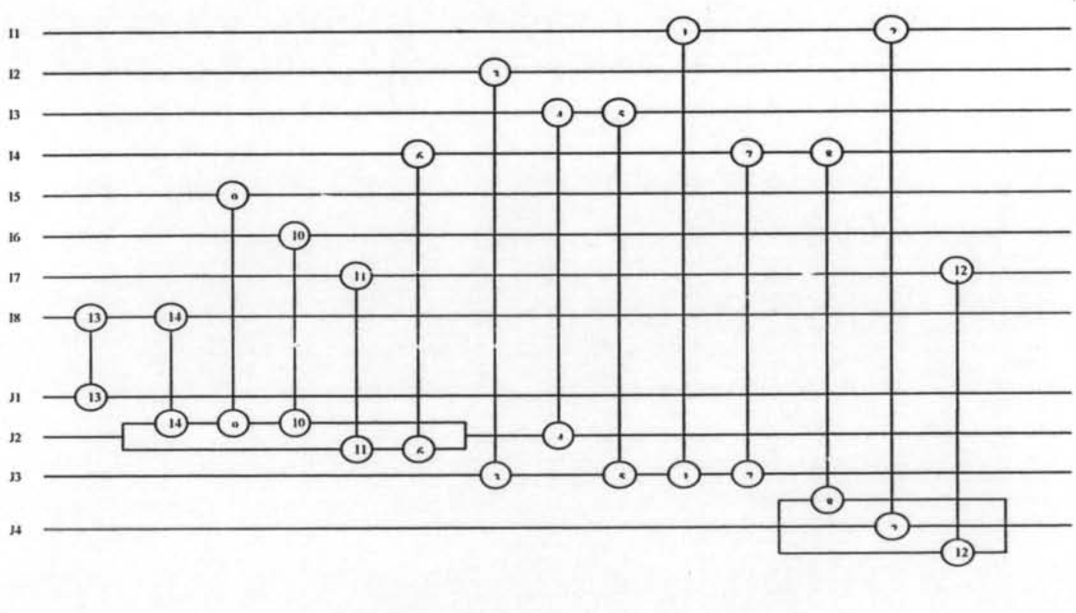


Figure 4.13 The retrofit heat exchange network for case study 4.6.

Table 4.20 Resulting of retrofit heat exchanger for case study 4.6

HE	Retrofit load kW	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	Cost $
1	1334.7002		32.143		32.143	9642.9
2	45665.298	2363.862	2363.862			
3	33000	1609.62	1610.68	1.059		317.7
4	1749.825		96.188		96.188	28856.4
5	5249.475	230.691	230.691			
6	10070.882	692.139	692.139			
7	416.223		8.702		8.702	2610.6
8	9512.895	339.797	337.334			
9	24999.8	1226.755	1248.511	21.755		6526.5
10	9000	224.915	249.819	24.904		7471.2
11	20999.44	1211	1211			
12	8999.76	141.471	138.96			
13	95000.35	1434.97	1432.729			
14	3180.053	53.311	32.965			
		9528.531	9685.723			55425.3

Table 4.21 Annual cost comparison between original and retrofit network for case study 4.6

Cost ($/yr)	Existing	Retrofit
Total utility cost	6330000	6211714.278
Total fixed and area cost		55425.3
Total cost	6330000	6267139.578
Cost saving (%)		62860.422 0.99%

4.3 Design of Heat Exchanger Network for Crude Fractionation Unit

4.3.1 Relationship between duty of pump around and steam of side stripper

Pump around which has greatly contributed to improve energy saving in the column is a device used to extract heat from the column, known as circulating refluxes. They consist of a liquid volume of drawn out from the column, cooled externally, reinjected to several trays and then reheated in the column. The partial revaporization or side stripper is used to eliminate the high volatile constituents from all these products. The stripper columns have 4 to 10 trays and the products are partially revaporized by the injection of steam. The revaporized fractions and the steam are recirculated in the atmospheric column. The steam is condensed at the top of the column and then separated by decantation in the reflux drum which has a liquid water drawn off.

Form Ji's Pro II model of crude fractionation column, shown in Figure 4.14, one calculator and one controller are added to calculate gap specification and control steam flowrate of side stripper, as shown in Figure 4.15.

The properties of crude which are set into the model such API gravity, TBP and light-end composition are shown in Table 4.22,4.23 and 4.24

Table 4.22 Feedstock used for design (Bagajewicz and Ji, 2001)

Crude	density (kg/m^3)	throughput (m^3/hr)
Light crude	845 (36.0 API)	795
Intermediate crude	889 (27.7 API)	795
Heavy crude	934 (20.0 API)	795

Table 4.23 TBP data (Bagajewicz and Ji, 2001)

vol%	temperature (°C)		
	Light crude	Intermediate crude	Heavy crude
5	45	94	130
10	82	131	190
30	186	265	290
50	281	380	450
70	382	506	640
90	552	670	N/A

Table 4.24 Light-end composition of crude (Bagajewicz and Ji, 2001)

component	vol%		
	Light crude	Intermediate crude	Heavy crude
ethane	0.13	0.1	0
propane	0.78	0.3	0.04
isobutane	0.49	0.2	0.04
n-butane	1.36	0.7	0.11
isopentane	1.05	0	0.14
n-pentane	1.3	0	0.16
Total	5.11	1.3	0.48

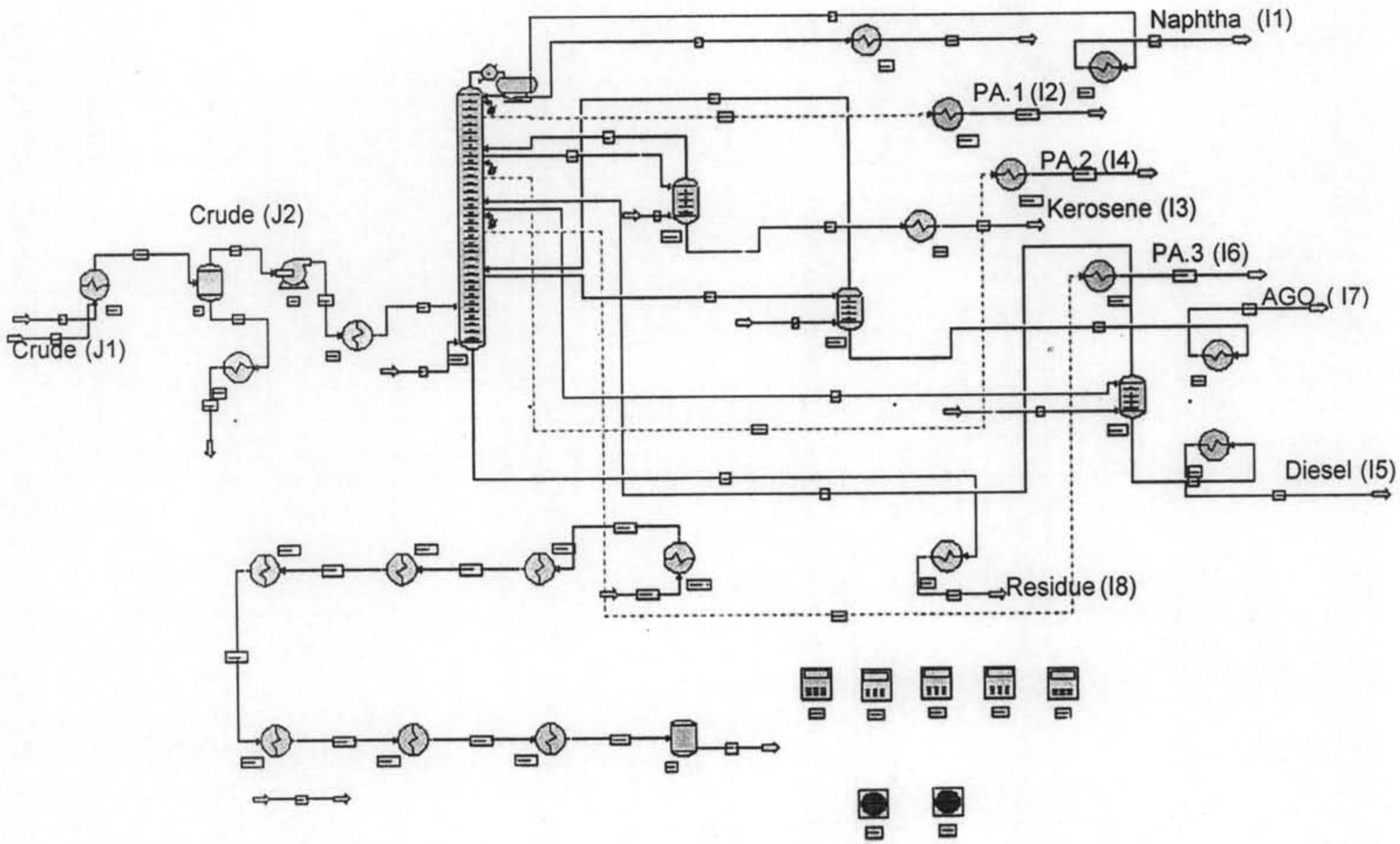


Figure 4.14 Ji's model of crude fractionation column

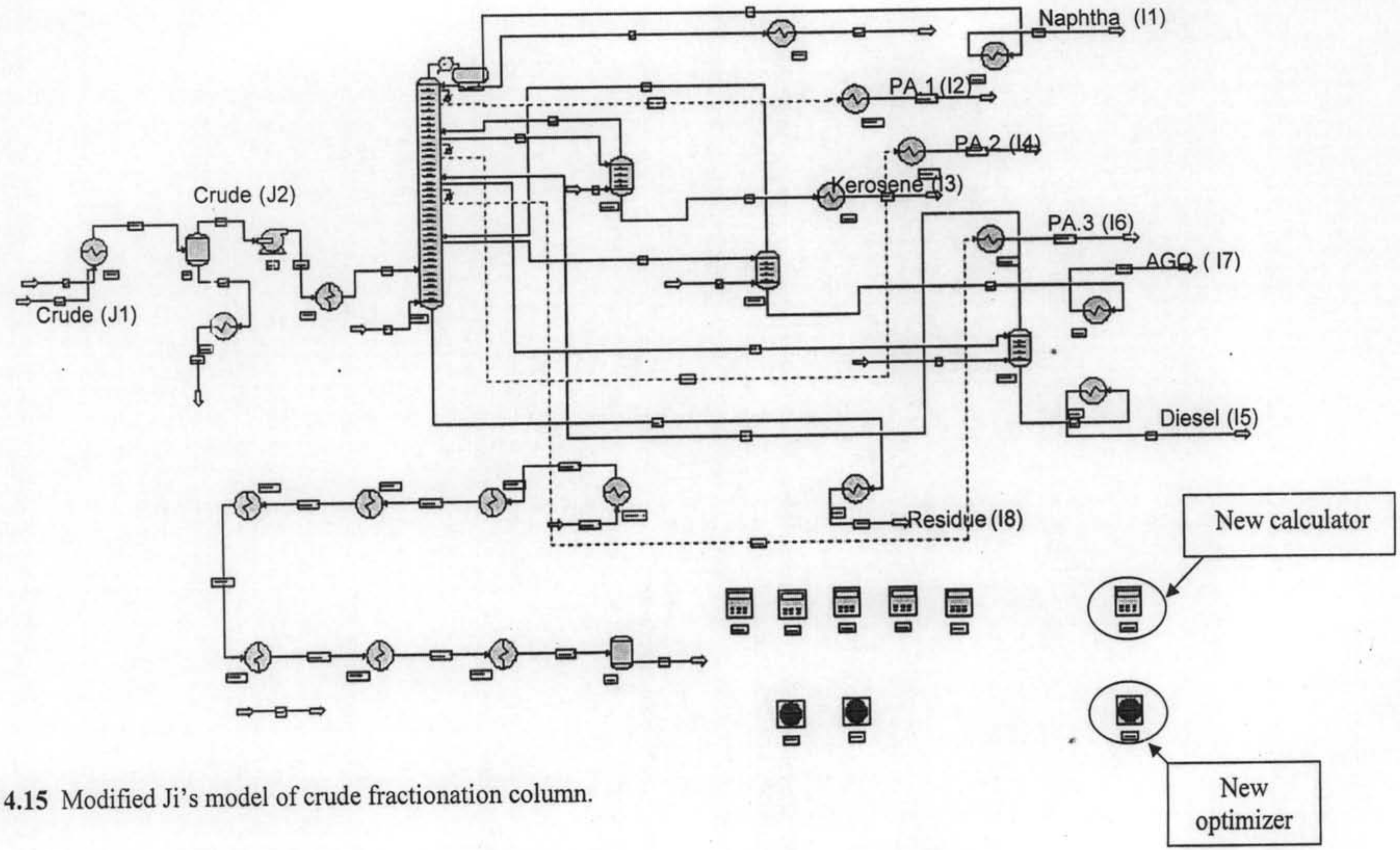


Figure 4.15 Modified Ji's model of crude fractionation column.

Figure 4.16 shows the setting of calculator to calculate the product gap specification by the values of product gap specification shown in Table 4.25. The steam of each side stripper is controlled by using controller. Figure 4.17 shows the controlling steam of side stripper by keeping product gap specification constant at 16.7

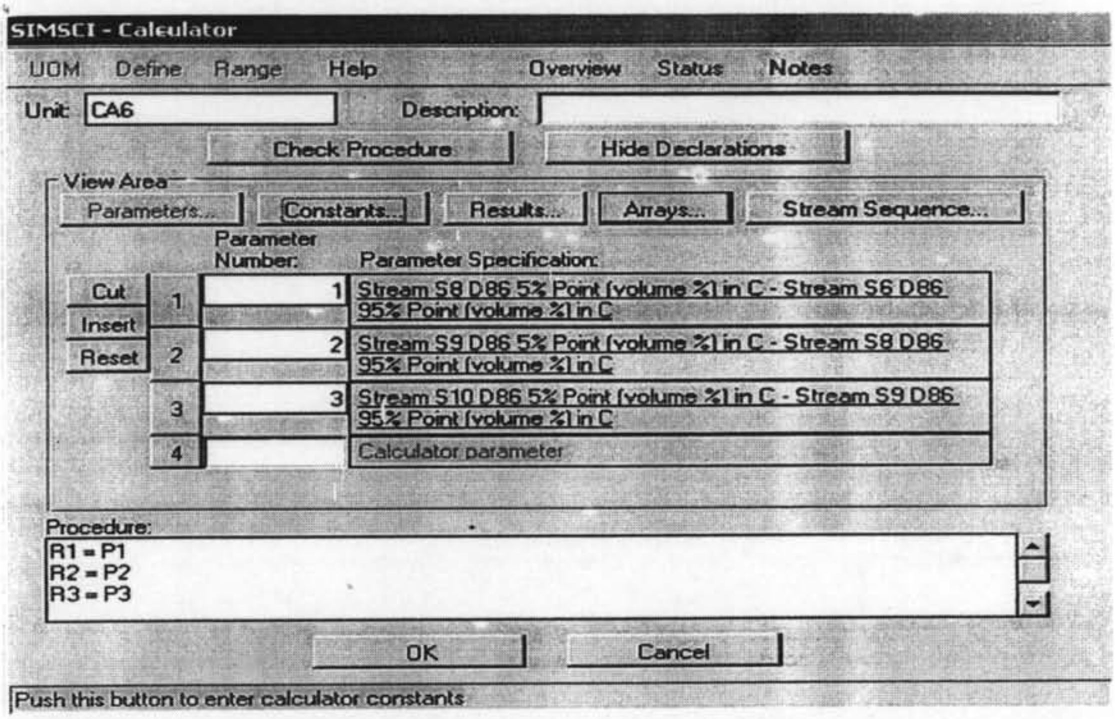


Figure 4.16 Setting calculator to calculate the gap specification.

Table 4.25 Product specifications and withdrawal tray (Bagajewicz and Ji, 2001)

product	Specification	withdrawal tray
naphtha	D86 (95% point) =182 °c	1
kerosene	D86 (95% point) =271 °c	9
diesel	D86 (95% point) =327 °c	16
gas oil	D86 (95% point) =377- 410 °c	25
kerosene - naphtha	(5-95)gap ≥ 16.7 °c	
diesel - kerosene	(5-95)gap ≥ 0 °c	
gas oil - diesel	(5-95)gap ≥ -5.6 °c to -11 °c	
feed tray		29
total trays		34

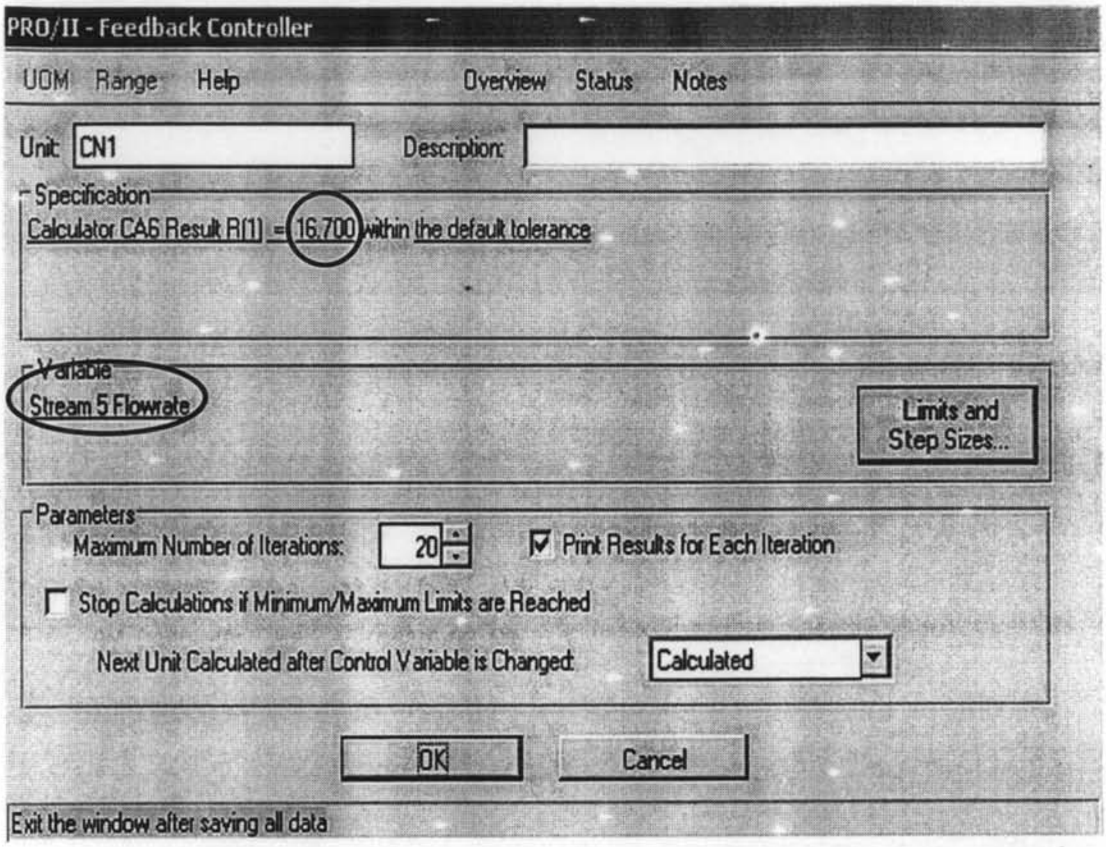


Figure 4.17 Setting controller to control steam of side stripper.

Table 4.26 Result for light crude

	flow rate (tone/hr)			Duty of PA (10^6 J/hr)				Steams of side stripping (ton/hr)		
case	I1 (PA 1)	I2 (PA 2)	I3 (PA 3)	PA1	PA2	PA3	total	5	4	3
1	703.323	81.03	38.173	130000	20000	8000	158000	1.236	1.683	2.216
2	651.702	121.372	40.612	120000	29500	8500	158000	1.428	1.792	2.213
3	547.858	170.818	87.627	100000	40000	18000	158000	1.869	2.232	2.249
4	495.506	195.998	113.067	90000	45000	23000	158000	2.154	2.496	2.265
5	416.508	217.047	176.192	75000	48000	35000	158000	2.68	3.17	2.294
6	282.192	288.737	248.628	50000	60000	48000	158000	3.955	4.252	2.321
7	171.755	357.079	308.068	30000	70000	58000	158000	5.525	5.36	2.33
8	57.921	438.159	371.877	10000	80000	68000	158000	7.771	6.795	2.342

To find the relationship between duty of each pump-around and steam of side stripper, the Table 4.26 shows the result of changing duty of each pump-around with the steam flowrate of each side stripper with the constant total duty of pump- around at 158,000 MJ/hr. From the result of Table 4.26 the regression gives the relation function between duty of pump-around and steam of side stripper as show in Table 4.27

Table 4.27 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
0.997945	5	2.82E-05	1.56E-05	5.91E-05	-3.81232
0.999121	4	-6.30E-05	-5.40E-05	-2.40E-05	11.14212
0.998536	3	-2.70E-05	-2.80E-05	-2.30E-05	6.491449

For the heavy and intermediate crude, the result and relationship are shown in Table 4.24 to 4.27

Table 4.28 Result for heavy crude

	flow rate (tone/hr)			Duty of PA (10^6 J/hr)				Steams of side Stripping (ton/hr)		
case	I1(PA 1)	I2(PA 2)	I3(PA 3)	PA1	PA2	PA3	total	5	4	3
1	317.011	117.88	45.724	60000	30000	10000	100000	2.436	3.844	1.686
2	267.684	141.217	69.53	50000	35000	15000	100000	2.792	4.563	1.716
3	217.331	166.079	93.984	40000	40000	20000	100000	3.246	5.384	1.739
4	165.692	192.757	119.147	30000	45000	25000	100000	3.794	6.363	1.758
5	112.384	221.626	145.106	20000	50000	30000	100000	4.428	7.533	1.77

Table 4.29 Relationship between duty of pump-around (PA1,PA2,PA3) and steam of side stripper (y) for heavy crude

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

R Square	Steam of side stripping	a	b	c	d
0.994585	5	-0.00111	-1.10E-05	-0.00211	90.47993
0.993800	4	0.001765	-4.40E-05	0.003773	-138.838
0.981603	3	0.003808	-0.00017	0.007794	-299.496

Table 4.30 Result for intermediate crude

	flow rate (tone/hr)			Duty of PA (10^6 J/hr)				Steams of side Stripping(ton/hr)		
case	I1(PA 1)	I2(PA 2)	I3(PA 3)	PA1	PA2	PA3	total	5	4	3
1	502.194	215.868	46.002	85000	50000	10000	145000	3.318	1.784	1.496
2	451.76	244.64	69.813	75000	55000	15000	145000	4.076	2.044	1.52
3	375.295	281.893	119.128	60000	60000	25000	145000	5.752	2.642	1.553
4	323.091	317.606	144.759	50000	65000	30000	145000	7.386	3.031	1.568
5	269.294	357.973	171.153	40000	70000	35000	145000	9.678	3.475	1.579

Table 4.31 Relationship between duty of pump-around (PA1,PA2,PA3) and steam of side stripper (y) for intermediate crude

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

R Square	Steam of side stripping	a	b	c	d
0.975263	5	0.000454	0.000878	0.000375	-83.4345
0.994657	4	3.69E-05	7.95E-05	7.14E-05	-6.10461
0.989269	3	4.11E-05	4.00E-05	4.52E-05	-4.44649

4.3.2 Preparation of the stream data for a heat exchanger network

From the modified Ji's model of crude fractionation column, the stream relationship data shown in Table 4.32 is used to find the heat exchanger network by MILP model.

Table 4.32 Stream data of each crude type

	Flow (tone/hr)			Tin ©			Tout ©		
Stream	Light crude	Intermediate crude	Heavy crude	Light crude	Intermediate crude	Heavy crude	Light crude	Intermediate crude	Heavy crude
I1	177.82	114.45	51.037	43.333	43.333	43.333	21.111	21.111	21.111
I3	120.15	78.005	119.59	219.68	194.068	209.74	21.111	21.111	21.111
I5	59.199	57.491	53.712	270.65	268.941	247.16	21.111	21.111	21.111
I7	102.41	42.276	23.518	318.51	309.625	293.37	21.111	21.111	21.111
I8	211.70	414.061	494.3	348.18	353.737	354.31	260	260	260
I2				182.57	175.86	183.45	104.44	104.444	104.44
I4				268.78	262.68	269.03	173.62	173.627	173.62
I6				308.51	310.658	310.30	232.22	232.222	232.22
I9				180	180	180	179	179	179
J1	752.59	787.57	823.44	21.111	21.111	21.111	137.77	137.78	137.78
J2	673.42	707.834	743.34	137.78	137.78	137.78	148.88	148.889	148.88
J3				35/20	35/20	35/20	45/30	45/30	45/30

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

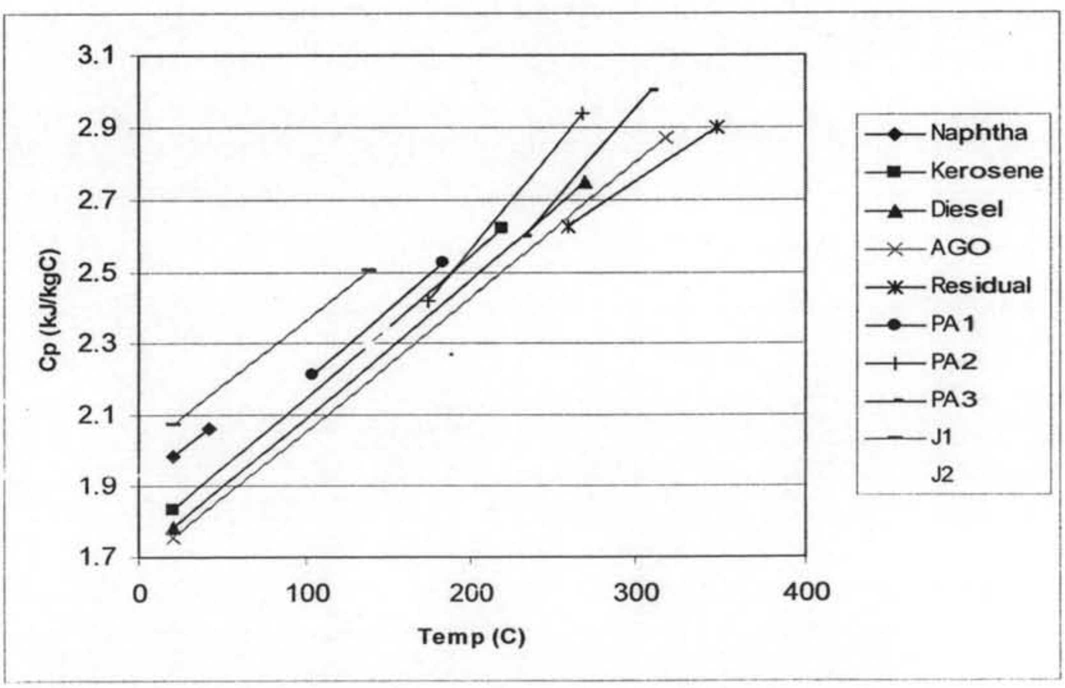


Figure 4.18 Changing of heat capacity with temperature for light crude.

Table 4.33 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

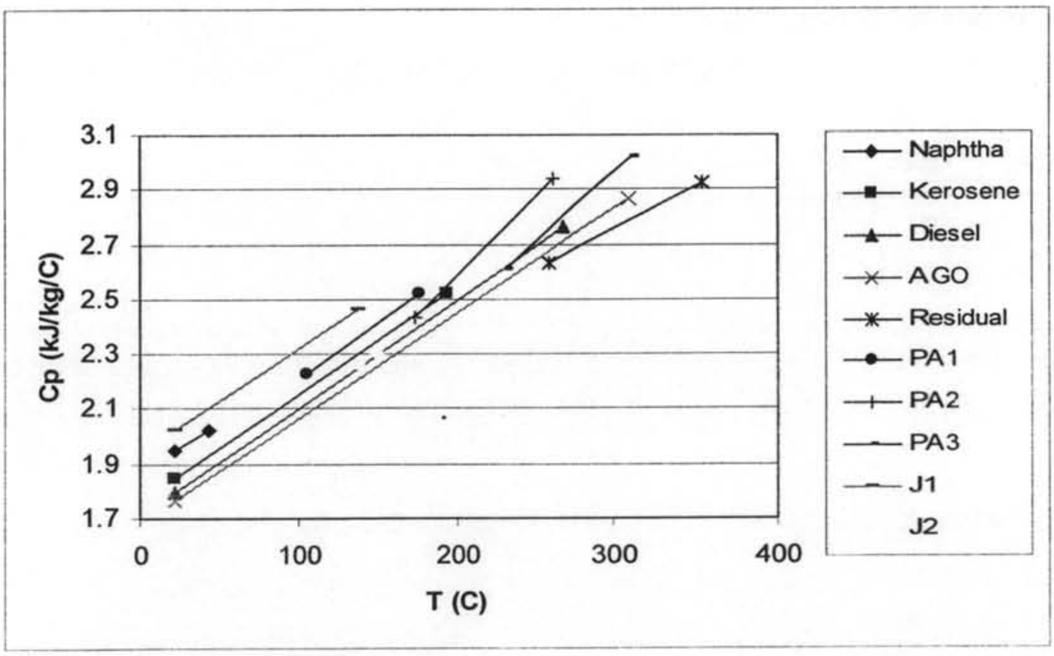


Figure 4.19 Changing of heat capacity with temperature for intermediate crude.

Table 4.34 Function of heat capacity for intermediate crude

Stream	Heat capacity
I1	Cp = (0.0035(T))+1.8729
I3	Cp = (0.0039(T))+1.7622
I5	Cp = (0.0039(T))+1.7161
I7	Cp = (0.0038(T))+1.6888
I8	Cp = (0.0031(T))+1.8296
I2	Cp = (0.0041(T))+1.8069
I4	Cp = (0.0057(T))+1.4494
I6	Cp = (0.0052(T))+1.4129
I9	Cp = 4.18
J1	Cp = (0.0037(T))+1.9461
J2	Cp = (0.0037(T))+1.7525
J3	Cp = 4.18

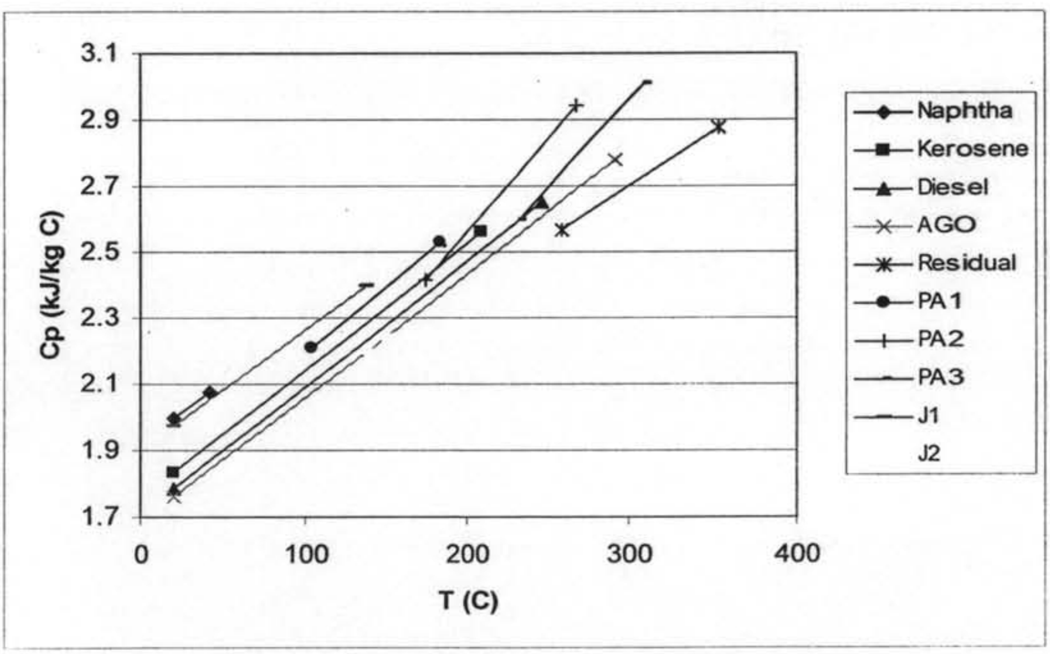


Figure 4.20 Changing of heat capacity with temperature for heavy crude.

Table 4.35 Function of heat capacity for heavy crude

Stream	Heat capacity
I1	Cp = (0.0035(T))+1.9259
I3	Cp = (0.0039(T))+1.7493
I5	Cp = (0.0038(T))+1.7061
I7	Cp = (0.0037(T))+1.6799
I8	Cp = (0.0032(T))+1.7235
I2	Cp = (0.004(T))+1.7943
I4	Cp = (0.0055(T))+1.4681
I6	Cp = (0.0052(T))+1.3896
I9	Cp = 4.18
J1	Cp = (0.0037(T))+1.8922
J2	Cp = (0.0037(T))+1.6935
J3	Cp = 4.18

Table 4.36 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 4.37 Cost of Steam Stripper

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

4.3.3 Heat exchanger network for crude fractionation column

From the stream data in previous part, the process stream data are taken into the GAMS model to find the heat exchanger network for crude fractionation column.

For type 1 and 2, the naphtha, pump-around number1, kerosene and diesel streams are set to not exchange heat with crude oil exiting from desalter. And pump-around number 2, pump-around number 3, gas-oil and residue streams are set to not exchange heat with crude oil before entering to the desalter. In the other hand, type 3 and 4 do not control the stream matching. In type 1 and 3, the temperatures of cold utility are 35°C at inlet and 45°C at outlet. In type 2 and 4, the temperatures of cold utility are 20°C at inlet and 30°C at outlet.

4.3.3.1 Heat exchanger of crude fractionation of light crude oil

The heat exchanger networks for light crude oil in each type are shown below.

(a) Heat exchanger network with constraints type 1

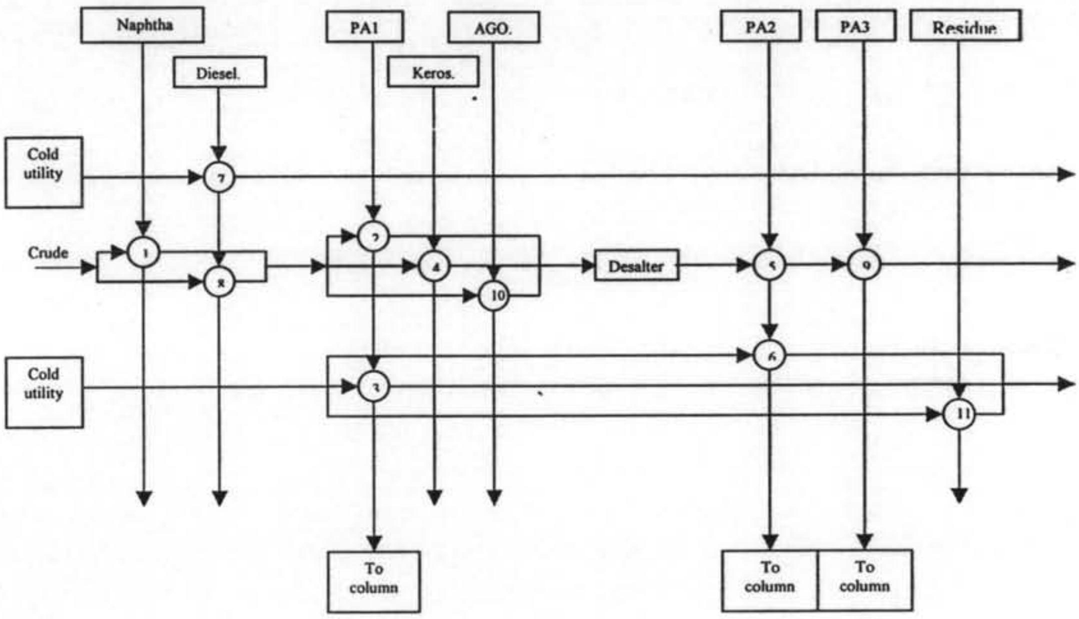


Figure 4.21 Heat exchanger network for light crude with constraints type 1.

(b) Heat exchanger network with constraints typc 2

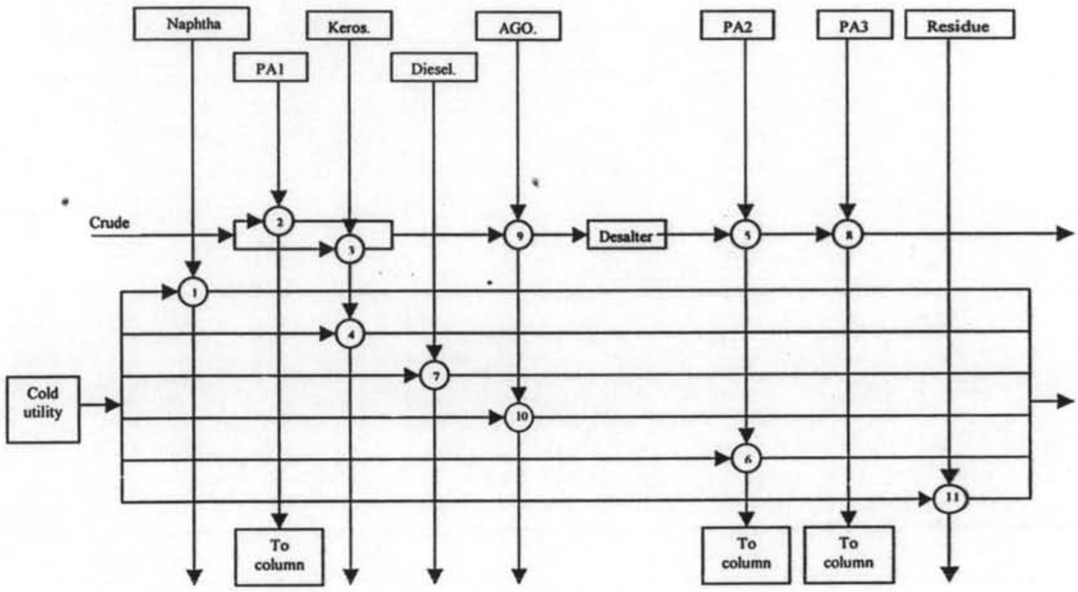


Figure 4.22 Heat exchanger network for light crude with constraints type 2.

(c) Heat exchanger network with constraints type 3

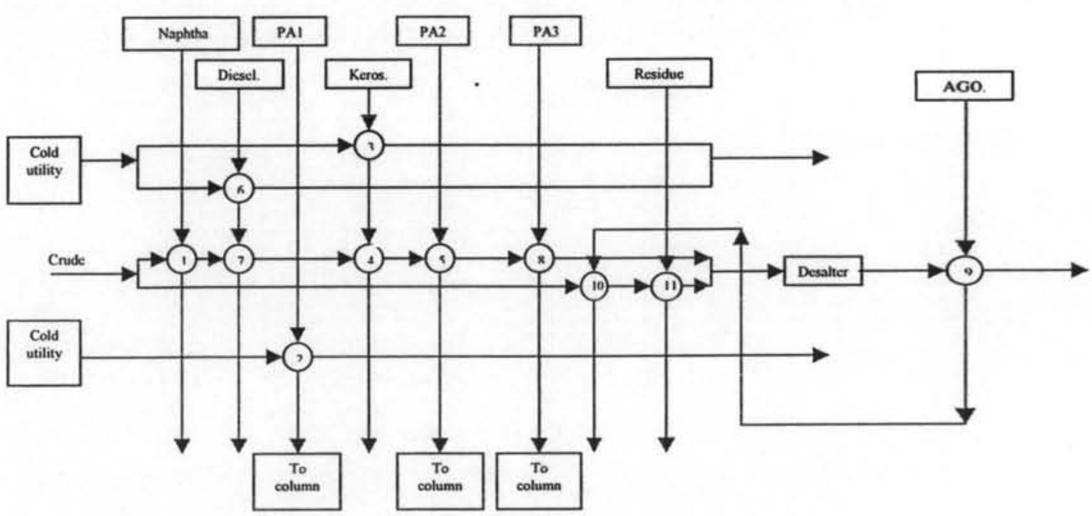


Figure 4.23 Heat exchanger network for light crude with constraints type 3.

(d) Heat exchanger network with constraints type 4

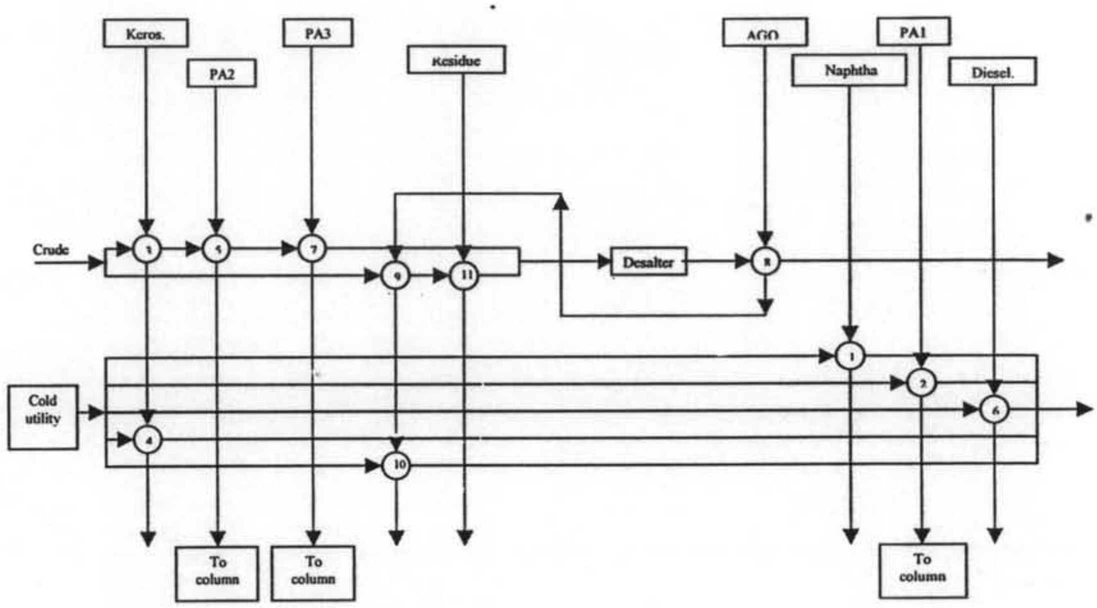


Figure 4.24 Heat exchanger network for light crude with constraints type 4.

The result for light crude oil in each type is shown in Table 4.38

Table 4.38 The result of light crude oil

		Utility (kg/hr)			Duty of pump-around (MJ/hr)		
Type	Total cost ($/yr)	Hot	Cold	Area (m^2)	PA1	PA2	PA3
1	1006601.271	0	15915.03	8383.131	130000.12	200000.2	8000.01
2	840306.109	0	15915.03	6245.331	130000.12	20000.02	8000.01
3	922402.692	0	15915.03	7300.26	90000.08	45000.04	23000.04
4	755450.859	0	15915.03	5154.022	90000.083	45000.04	23000.04

The result shows the same amount of cold utility is used in all cases but the costs is different. When cold utility, from type 1 and 3 the ΔT_{lm} value is smaller than cold utility from type 2 and 4, so the area of cooler of type 1 and 3 is higher than type 2 and 4. In case of type 3 and 4 the area of heat exchanger is lower than type 1 and 2 because in case of type 3 and 4, the high temperature of hot streams such as pump-around 2 and 3 are matched with cold stream this makes the ΔT_{lm} is high so the area of heat exchanger is small when compared to case that pump-around 1 exchange with cold streams. From this reason the total area of heat exchanger in case of type 3 and 4 is smaller than one in the case of type 1 and 2.

4.3.3.2 Heat exchanger of crude fractionation of intermediate crude oil

The heat exchanger networks for intermediate crude oil in each type are shown below.

(a) Heat exchanger network with constraints type 1

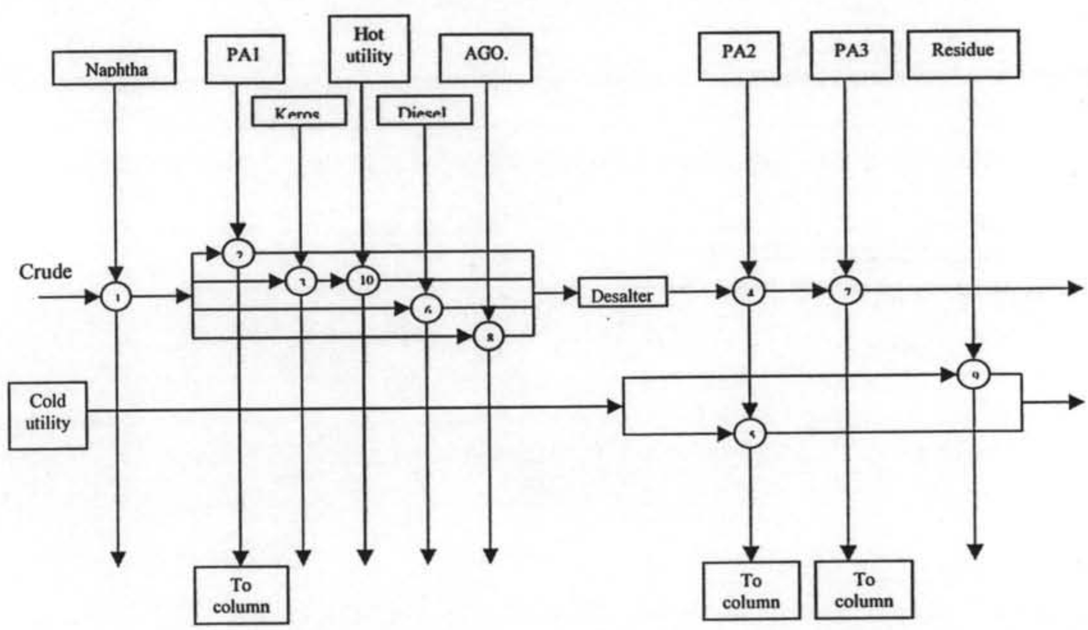


Figure 4.25 Heat exchanger network for intermediate crude with constraints type 1.

(b) Heat exchanger network with constraints type 2

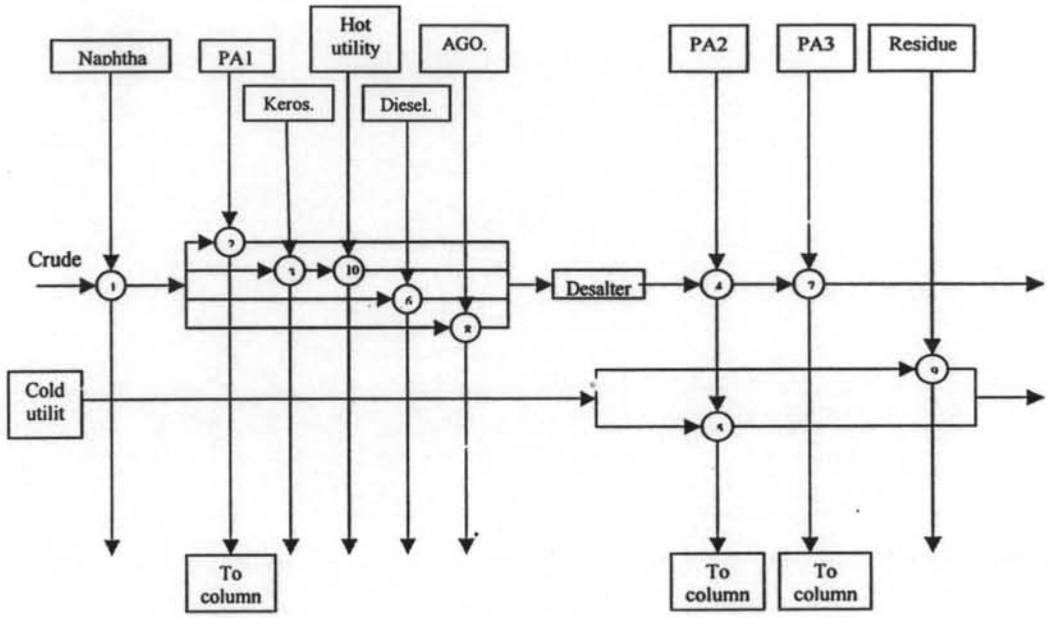


Figure 4.26 Heat exchanger network for intermediate crude with constraints type 2.

(c) Heat exchanger network with constraints type 3

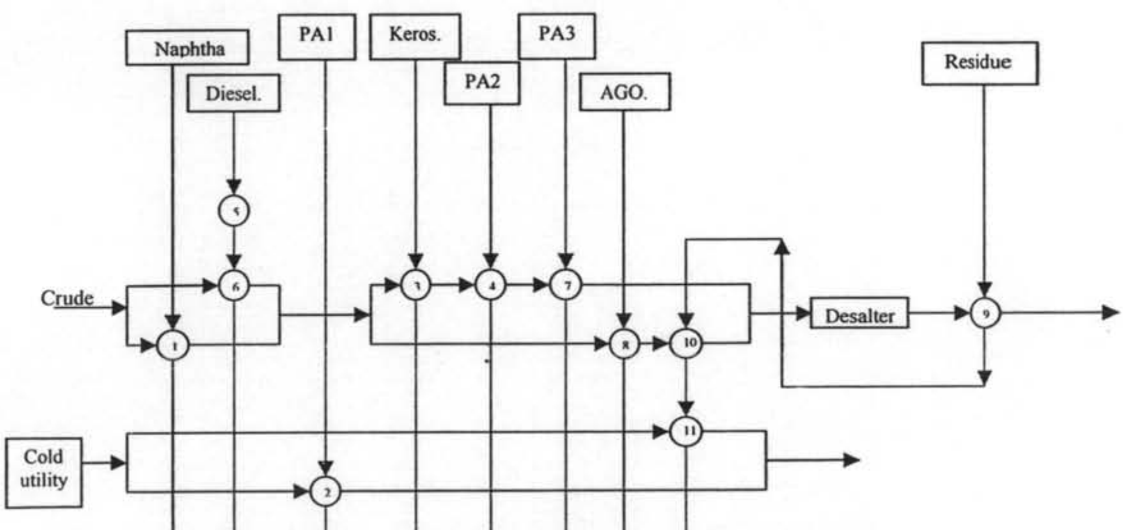


Figure 4.27 Heat exchanger network for intermediate crude with constraints type 3.

(d) Heat exchanger network with constraints type 4

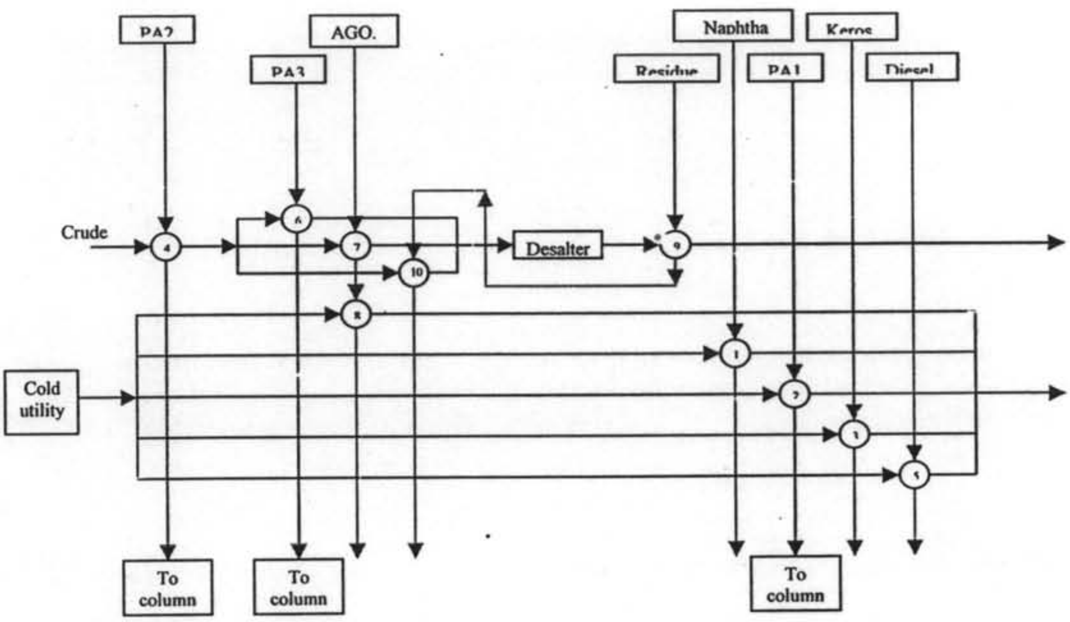


Figure 4.28 Heat exchanger network for intermediate crude with constraints type 4.

The detail of each type of heat exchanger network for intermediate crude oil is the same as the light crude oil. The result for intermediate crude oil in each type is shown in Table 4.39

Table 4.39 The result of intermediate crude oil

		Utility (kg/hr)			Duty of pump-around (MJ/hr)		
Type	Total cost ($/yr)	Hot	Cold	Area (m^2)	PA1	PA2	PA3
1	1423066.831	23055.81	15012.58	8166.93	84999.899	49999.92	9999.99
2	1417756.318	23055.81	15012.58	8098.66	84999.899	49999.92	9999.99
3	730950.510	0	12707.00	5604.61	39999.96	69999.89	34999.95
4	608568.520	0	12707.00	4099.36	39999.96	69999.89	34999.95

The result from type 1 and 2, hot utility is used but in type 3and 4 do not need the hot utility because the heat demand in cold stream before entering to the desalter is higher than the supplied heat from process streams. For type 3 and 4, it does not control the streams matching so it can use heat from the residue, pump-around 2 and 3 streams to exchange with cold stream. The reason that type 3 is cheaper than type 1 are the area cost that is the same the reason as shown in case of light crude and the hot utility that do not use in type 3. The total cost in type 4 is cheaper than type 3 because of the ΔT_{lm} value, that have a effect on the area cost as shown in the light crude.

4.3.3.3 Heat exchanger of crude fractionation of heavy crude oil

The heat exchanger networks for heavy crude oil in each type are shown at below.

(a) Heat exchanger network with constraints type 1

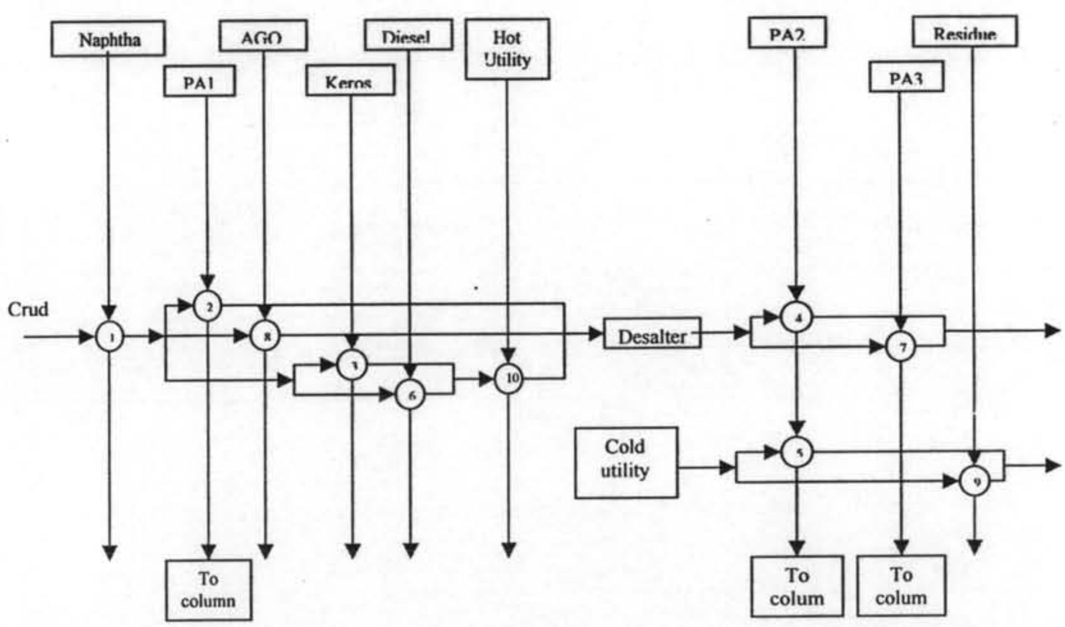


Figure 4.29 Heat exchanger network for heavy crude with constraints type 1.

(b) Heat exchanger network with constraints type 2

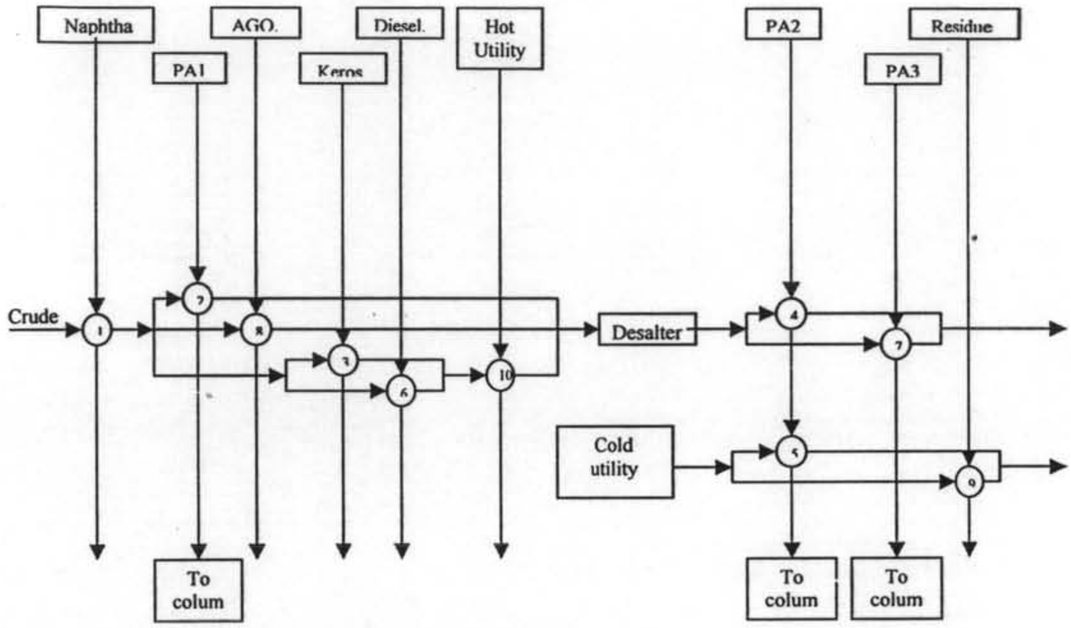


Figure 4.30 Heat exchanger network for heavy crude with constraints type 2.

(c) Heat exchanger network with constraints type 3

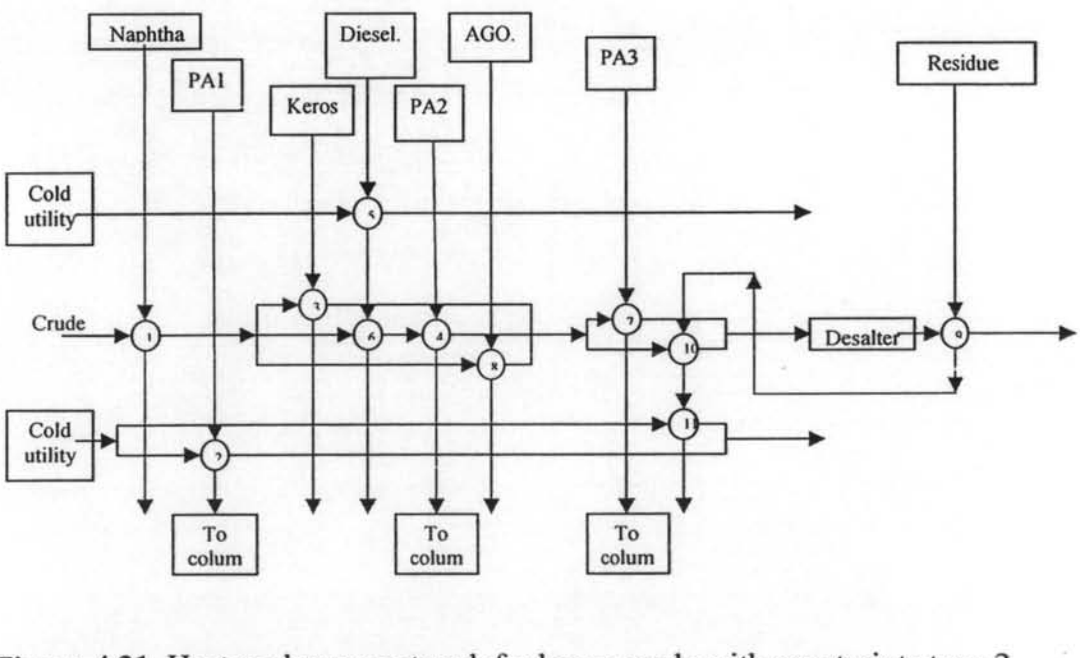


Figure 4.31 Heat exchanger network for heavy crude with constraints type 3.

(d) Heat exchanger network with constraints type 4

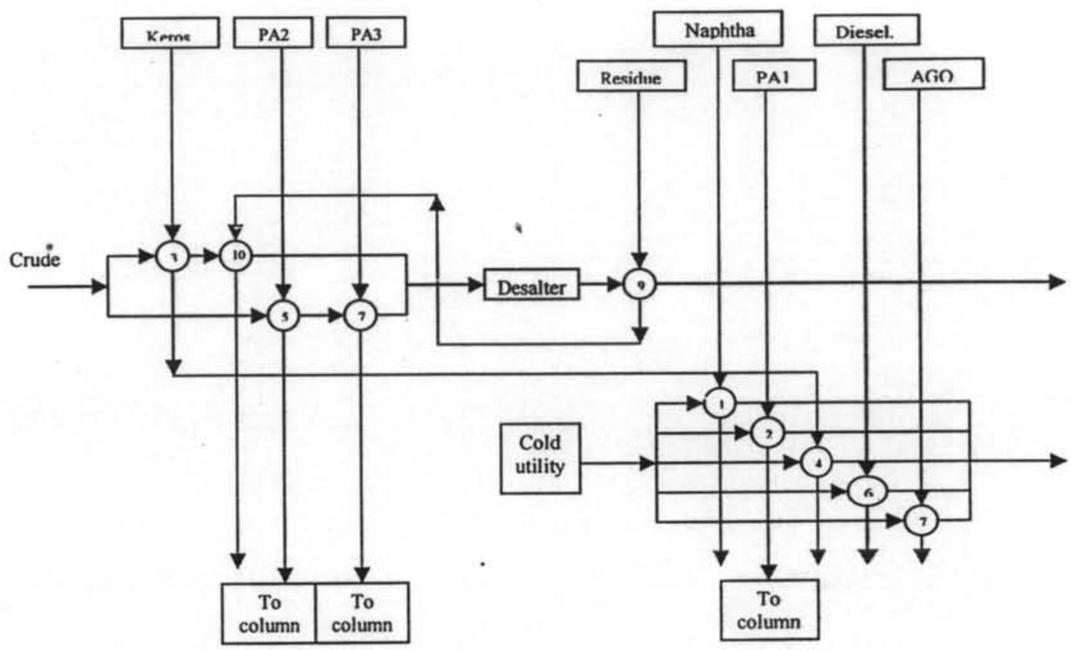


Figure 4.32 Heat exchanger network for heavy crude with constraints type 4.

The detail of each type of heat exchanger network for heavy crude oil is the same as the two previous crude types. The result for heavy crude oil in each type is shown in Table 4.40.

Table 4.40 The result of heavy crude oil

Type	Total cost ($/yr)	Utility		Area (m^2)	Duty of pump-around (MJ/hr)		
		Hot	Cold		PA1	PA2	PA3
1	2176366.059	64121.64	14965.94	7434.82	49999.89	35000.06	14999.98
2	2171960.551	64121.64	14965.94	7378.19	49999.89	35000.06	14999.98
3	621134.225	0	8553.784	5186.61	19999.96	50000.09	29999.96
4	523312.127	0	8553.784	3997.09	19999.96	50000.09	29999.96

The result of type 1 and 2 need to use hot utility but type 3 and 4 do not use because the supplied heat for exchanging with cold stream before entering to desalter is not enough so it want to use hot utility. Total cost for type 2 and 4 is cheaper than type 1 and 3 because the temperature of cold utility in type 2 and 4 is lower than type 1 and 3 that make the area of heat exchanger in type 2 and 4 is lower than type1 and 3.

4.4 Retrofit of Heat Exchanger Network for Crude Fractionation Unit

4.4.1 Retrofit of heat exchanger network for light crude

This case study uses the stream data from light crude. The existing heat exchanger network configuration, Figure 4.33, consumes 71,270.5 kW of hot utility and 223,643.8 kW of cold utility. The retrofit result is shown in Figure 4.34. Two new exchanger units are installed, area of 733.352 m^2 is added to existing heat exchanger and 6,403.619kW of hot utility and 165,553.86kW of cold utility are required. The model can generate the retrofit network with total cost saving of 123.91% or 935.2131k$/yr.

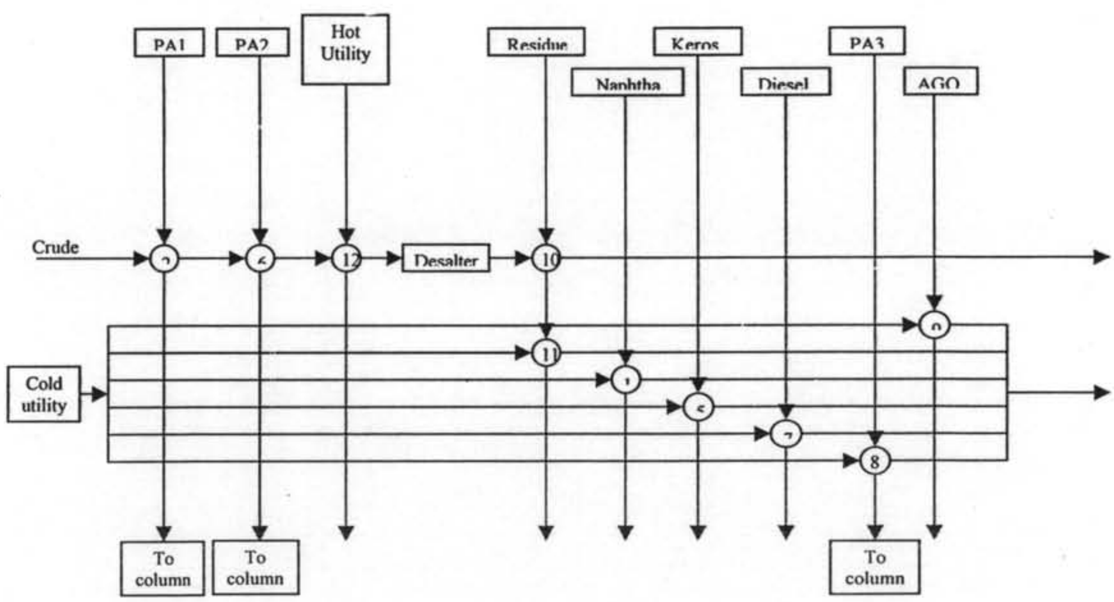


Figure 4.33 The existing heat exchanger network for light crude.

Table 4.41 Resulting of retrofit heat exchanger for light crude

HE	Retrofit load kW	Original Area m²	Retrofit Area m²	Added Area m²	New HE. m²	Cost $
1	8049.825	518.2402	515.685			
2	116415.449	1267.954	2000	732.046		125472.7
3	3584.656		29.837		29.837	10405.96
4	47174.532		1043.016		1043.016	184064.8
5	6508.687	966.08	637.226			
6	29500.021	470.4239	429.001			
7	33872.055	682.7927	634.109			
8	8500.015	184.5678	67.99			
9	71270.508	941.5554	852.919			
10	17194.963	188.1183	189.425	1.306		223.8484
11	33768.113	167.4541	167.062			
12	6403.619	1300.546	145.123			
		6687.7324	6711.393	733.352		320167.3

Table 4.42 Annual cost comparison between original and retrofit network for light crude

Cost ($/yr)	Existing	Retrofit
Total utility cost	1689947.64	434567.2
Total fixed and area cost		320167.3
Total cost	1689947.64	754734.5
Cost saving		935213.1
(%)		123.91%

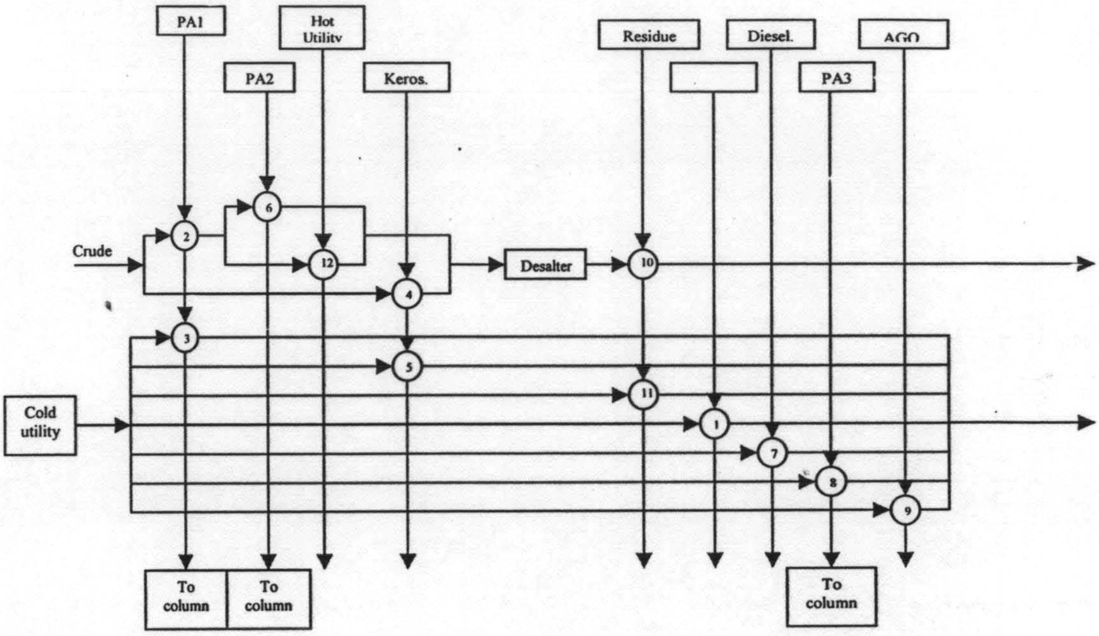


Figure 4.34 The retrofit heat exchanger network for light crude.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

A new MILP formulation for both design and retrofit of heat exchanger networks was presented. The grass-root model is used to design heat exchanger network for small and large networks, of the crude fractionation unit. For the retrofit of heat exchanger networks, a new MILP formulation takes into account of the retrofit options involving modification of the existing structure and new exchanger placement.

First part of this work covered the new design for heat exchanger network. The results show that the MILP model provides an optimal network structure for complex hot and cold process streams. For second part, it covered heat exchanger networks retrofit. The crude fractionation unit is used as the case study and the retrofit solution can achieve 78.23% annual cost savings or 5.37 M$/yr with three new exchanger units and three additional shells. For the last part, it covered the design of the heat exchanger network for crude fractionation unit to find the effective network and appropriate value of each pump around flowrate. The results show that the network with the constraints of the low temperature of cold utility and not matching streams got the lowest cost.

From this study, it is suggested that the heat exchanger network being investigated should be simplified in model assumption, non-isothermal mixing, stream splitting and allowed/forbidden matches. This will be enable the user to stay in control of the optimization, by being able to understand the results. For the design of the heat exchanger network of crude fractionation unit, there are some parameters that need to be adjusted such as the heat capacity value which should be linear function with temperature to get the result from the MILP model.

In general, mathematical models have the advantage of finding optimal solutions. But the major difficulty in this proposed algorithm is to guarantee the network is feasible in the case where there is unsuitable number of temperature intervals. We commonly use higher number of temperature intervals of hot process streams than one of cold process streams, because this will give more heat transfer possibility. In contrast, lower number of temperature intervals of hot stream than one of cold stream would come with less heat transfer room. However, larger number of temperature intervals for hot stream will bring the model become complicate and difficult to find a feasible solution.