CHAPTER VII

RESULT AND DISCUSSION

Results are shown and discussed simultaneously in five steps as follows:

1. The base model of the topping unit based on two design cases.
2. The base model verified by actual operating data.
3. Bottlenecks of the topping unit at 50 and 60 KBD.
4. Debottlenecking at 50 and 60 KBD.
5. Economic evaluation of debottlenecking.

The Base Model of the Topping Unit Based on Two Design Cases.

The topping unit has two design cases; (A) Arabian light 100% at 40 KBD and (B) Qatar and Tapis 70:30%vol at 40 KBD. These cases are used to model the topping unit by using PRO/II. In modeling, the topping unit must be divided into three sections -- (1) separation, (2) heat exchanger network (HEN) , and (3) utility -- , and modeled sequentially as shown in Figure 7.1.

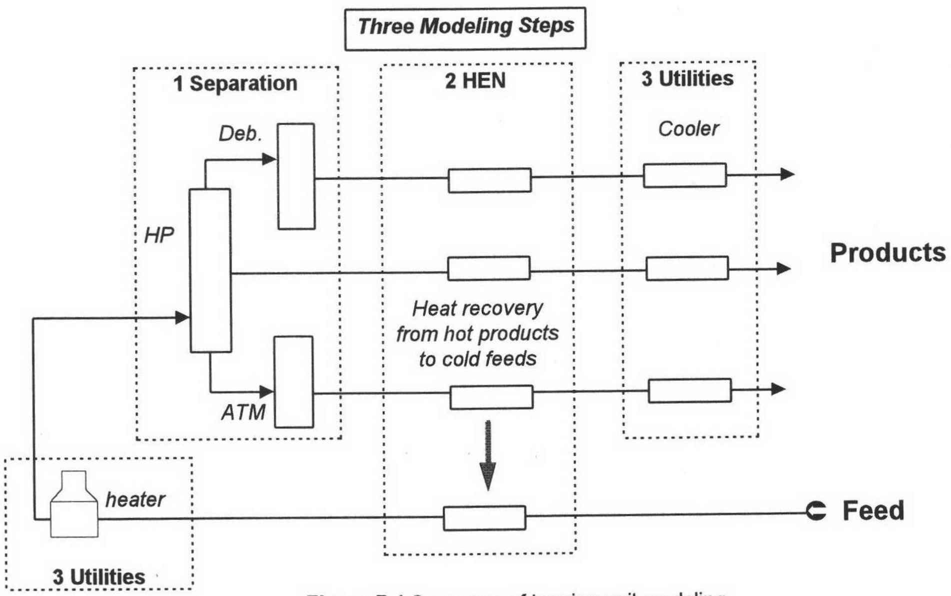


Figure 7.1 Sequence of topping unit modeling

The separation section consists of three distillation columns; HP fractionator, ATM fractionator, and Debutanizer. To generate the base model of these columns, theoretical trays are identified first. After that, their tray efficiencies are known. With these efficiencies in Table 7.1 and Figure 7.2, the base model can match predicted results of product rates and column temperature profile with the design data of case A and B within ± 3.5% error (mostly, within ±2%error), shown in Table 7.2. Also, predicted product properties (ASTM, flash point, sp.gr., etc.) are matched with the product specification shown in Table 7.3. These efficiency factors searched by modeling ranges 50% to 66% corresponding with the recommended data [3,31].

Table 7.1 Efficiency of three columns in topping unit for two design cases (A and B)

Unit Section	Actual Tray	Theoretical Tray	Overall Efficiency
HP fractionator			
• Naphtha - Kerosene	16	11	68.8
• Kerosene - Diesel	10	8	80.0
• Diesel - Feed	5	2	40.4
• Feed - Bottom	3	1	33.3
Total	**34**	**22**	**64.7**
ATM fractionator			
• Light - Heavy Gas Oil	11	5	45.5
• Heavy Gas Oil - Feed	6	4	66.7
• Feed - Reduced Crude	3	2	66.7
Total	**20**	**11**	**55.0**
Debutanizer			
• LPG - Feed	13	6	46.2
• Feed - Stabilized Naphtha	23	18	78.3
Total	**36**	**24**	**66.7**

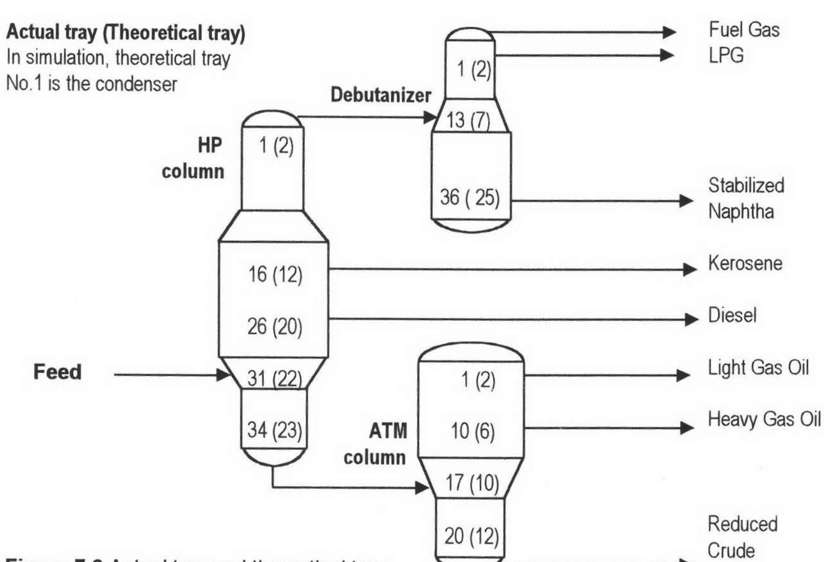


Figure 7.2 Actual tray and theoretical tray in topping unit.

Table 7.2 Product flowrate and temperature profile.

(a) Product Flowrate (m^3/h)

Unit	Case A : Arabian light 100%vol			Case B : Qatar + Tapis (70 +30%vol)		
	Design	Simulated	% Error	Design	Simulated	% Error
HP fractionator						
• Naphtha	59.6	59.7	0.2	63.7	63.9	0.3
• Kerosene	36.4	36.4	-	44.5	44.5	-
• Diesel	46.2	46.2	-	53.3	53.3	-
• Bottom	125.4	125.4	-	80.7	80.7	-
ATM fractionator						
• Light Gas Oil	9.3	9.5	1.6	7.5	7.5	-
• Heavy Gas Oil	15.8	15.7	-0.4	16.9	17.0	0.6
• Reduced Crude	100.5	100.2	-0.3	56.4	56.1	-0.5
Debutanizer						
• Fuel Gas (kg/h)	9.8	9.8	-	225.1	226.0	0.4
• LPG	3.5	3.6	1.1	9.1	9.1	-
• Stabilized Naphtha	56.0	56.0	-	54.2	54.4	0.4

(b) Temperature Profile (°C)

Unit	Case A : Arabian light 100%vol			Case B : Qatar + Tapis (70 +30%vol)		
	Design	Simulated	% Error	Design	Simulated	% Error
HP fractionator						
• Naphtha	45	45	-	45	45	-
• Kerosene	279	274	-1.9	268	267	-0.3
• Diesel	303	304	0.2	303	294	-2.9
• Bottom	373	373	-	353	353	-
ATM fractionator						
• Light Gas Oil	45	45	-	45	45	-
• Heavy Gas Oil	316	316	-	291	291	-
• Reduced Crude	356	355	-0.3	325	332	2.1
Debutanizer						
• Fuel Gas	49	49	-	45	45	-
• LPG	49	49	-	45	45	-
• Stabilized Naphtha	168	166	-1.2	179	185	3.4

Table 7.3 Product specification of design cases (A and B).

Product Specification (unit = °C)	HP Fractionator			ATM Fractionator	
	Naphtha	Kerosene	Diesel	Light & Heavy Gas Oil	Reduced Crude
TBP cut	C5 - 154	154 - 235	235 - 330	330 - 385	385+
TBP (end point) (max.)	180				
ASTM (max.)					
10%vol		205			
90%vol			370		
end point	185	300			
Gap. ASTM 95%Naph. with 5%Kero.	**Min. = 10**				
Overlap ASTM 95% Kero. with 5%Diesel		**Max. = 20**			
Flash point (min.)		40	55	55	60
Sp.Gr. (max.)		0.84	0.82 -0.9	0.9	

After the separation section has been modeled, the HEN can be modeled in the next step. To model HEN, the configurations of heat exchangers are used in rating by PRO/II. The results of rating HEN (temperature profile), shown in Table 7.4, correspond with the design data cases within ±5%error. The final step is the utility modeling (coolers and heaters) which is the same procedure as the HEN rating. Detail data such as temperature, pressure, flowrate, and duty are shown in the process flow diagram (PFD) in Appendix. Combine three section models to the complete base model or base flowsheet which must be verified by actual data.

Table 7.4 The temperature profile in HEN of two design cases (A and B)

Unit Number.	Crude Outlet Temperature (°C)					
	Case A			Case B		
	Design	Simulated	%Error	Design	Simulated	%Error
1	97	97	-	98	98	-
2	112	115	2.7	112	112	-
3	132	133	0.8	133	133	-
4	152	153	0.7	152	152	-
5	162	163	0.6	162	162	-
6	179	180	0.6	177	178	0.6
7	188	189	0.5	186	188	1.1
8	222	223	0.5	199	199	-
10	235	235	-	213	214	0.5
9	257	257	-	234	238	1.7
11	289	288	0.3	252	259	1.6

The Base Model Verified by Actual Operating Data.

The model based on design cases is verified by actual data case (40%vol of Phet + 60%vol of Tapis at 40 KBD). The results of the base model compare with the actual operating data shown in Table 7.5. Most predicted product flowrate correspond with the actual data about less than 5% error. But, the flowrate of light gas oil and the temperature of heavy gas oil are more than 5% error. These errors may be the result of the plant instrument measurement errors. For product spec, the predicted data valid the product specification in Table 7.3, and correspond with the lab data -- ASTM 95%vol of kerosene equals 223°C and the flash point of a blending stream of diesel and gas oil equals 60°C (simulated 61°C). When the model has been verified by actual data, it can be used to identify capacity bottlenecks and debottleneck them.

Table 7.5 Compare the predicted results of the base model with the actual operating data.

Actual Case : Phet + Tapis (40+60%vol) at 40 KBD

(a) Predicted results of three column products -- flowrate and temperature.

Unit	Product Flowrate (m^3/h)			Temperature (^oC)		
	Actual	Simulated	% Error	Actual	Simulated	% Error
HP fractionator						
• Naphtha	67.7	67.9	0.3	51	51	-
• Kerosene	37.5	37.5	-	253	250	-1.2
• Diesel	47.5	47.5	-	277	273	-1.4
• Bottom	119.6	119.7	0.1	341	336	-1.5
ATM fractionator						
• Light Gas Oil	5.1	5.6	8.4	70	70	-
• Heavy Gas Oil	8.9	8.4	-4.9	281	255	-9.3
• Reduced Crude	105.6	105.6	-	324	309	-4.6
Debutanizer						
• Fuel Gas (kg/h)	No data	5.0	-	43	44	2.3
• LPG	7.0	7.0	-	43	44	2.3
• Stabilized Naphtha	60.5	60.9	0.7	171	174	1.7

(b) Temperature profile of crude in HEN of actual case.

Unit Number.	Crude Outlet Temperature (^oC)		
	Actual Case		
	Actual	Simulated	%Error
1	85	85	-
2	105	105	-
3	123	121	-1.6
4	133	133	-
5	143	137	-4.2
6	158	152	-3.8
7	169	164	-3.0
8	192	199	3.6
10	201	207	3.6
9	219	222	1.4
11	244	244	-

Bottlenecks of the Topping Unit at 50 and 60 KBD.

The base model is used to simulate the topping unit to predict how it will behave if its feeds are increased to 50, 60 KBD. By simulating the base model, the limits or bottlenecks in each equipment can be identified. These column bottlenecks are shown in Table 7.7 which show the column bottlenecks in each case study. The case study includes three cases:

1. Case A : Arabian light 100%
2. Case B : Qatar + Tapis (70 + 30 % vol.)
3. Case C : Oman + Tapis (38 +62 %vol)

In Table 7.7, the bottleneck trend of these cases both 50 and 60 KBD are obvious as follows:

Column bottlenecks

Column bottlenecks is the tray flooding determined by flooding percentage which is more than 85%flooding. The following bottlenecks are listed by the maximum bottleneck cases:

1. In case A, the maximum bottlenecks of ATM column occur because crude A (the heavy crude) has the maximum heavy products of three crudes or cases (shown in Table 7.6).
2. In case B, the maximum bottlenecks of Debutanizer occur because crude B (the light crude) has the maximum light products of three crudes.
3. In case C, the maximum bottlenecks of HP column and diesel stripper column occur because crude C (the middle crude) has the maximum middle products of three crudes.

Table 7.6 Yield percentage of three crudes.

Unit %vol.

	Products	Case A : Arabian light	Case B : Qatar + Tapis	Case C : Oman + Tapis
Light products	Total Naphtha	21.5	**25.6**	18.3
Middle products	Kerosene & Diesel	31.2	40.7	**49.3**
Heavy products	Gas Oil & Reduced crude	**47.3**	33.6	32.3

HEN bottlenecks

In all cases, the HEN bottlenecks occur in most heat exchangers. They include two problems:

1. Area transfer is inadequate to achieve a target temperature.
2. High pressure drop in tube side is more than 1 bar.

Utilities bottlenecks

Utilities bottlenecks are divided into two types; heaters and coolers.

1. Heater duty is not enough to heat a crude feed to its flash point. This problem occurs in all cases at both capacities.
2. Cooler bottlenecks include two problems: inadequate area and high pressure drop in tube side(more than 1 bar). The maximum cooler bottlenecks occur as similarly as the column bottlenecks:
   - Case A bottlenecks occur in ATM product streams.
   - Case B bottlenecks occur in Debutanizer product streams.
   - Case C bottlenecks occur in HP product streams.

Table 7.7 Bottlenecks of Topping Columns for Case A, B, and C.

Case A

Unit	50 KBD		60 KBD	
	Theoretical Tray No.	Max. %Flooding	Theoretical Tray No.	Max. %Flooding
HP fractionator	9 - 10	101	2 - 14, 19 - 20	121, 94
ATM fractionator	**3 - 6**	**94**	**3 - 9**	**114**
Debutanizer	-	-	-	-

Case B

Unit	50 KBD		60 KBD	
	Theoretical Tray No.	Max. %Flooding	Theoretical Tray No.	Max. %Flooding
HP fractionator	8 - 11	106	2 - 14, 19 - 20	120, 95
ATM fractionator	3 - 6	94	3 - 9	108
Debutanizer	-	-	**2 - 5**	**92**

Case C

Unit	50 KBD		60 KBD	
	Theoretical Tray No.	Max. %Flooding	Theoretical Tray No.	Max. %Flooding
HP fractionator	**2 - 16, 19 - 20**	**133, 95**	**2 - 20**	**160**
ATM fractionator	-	-	3 - 8	95
Debutanizer	-	-	-	-
Diesel Stripper	-	-	**1**	**93**

Maximum Column Bottlenecks

Unit	50 KBD			60 KBD		
	Theoretical Tray No.	Max. % Flooding	Case	Theoretical Tray No.	Max. % Flooding	Case
HP fractionator	**2 - 16, 19 - 20**	**133, 95**	**C**	**2 - 20**	**160**	**C**
ATM fractionator	**3 - 6**	**94**	**A**	**3 - 9**	**114**	**A**
Debutanizer	-	-	-	**2 - 5**	**92**	**B**
Diesel Stripper	-	-	-	**1**	**93**	**C**

Debottlenecking at 50 and 60 KBD.

Sequence of debottlenecking is similar to the sequence of bottleneck identification--(1) separation or column, (2) HEN, and (3) utilities (heaters and coolers) -- shown as follows:

Column debottlenecking

Column debottleneck is the first task because column products are heat sources for HEN. Two alternatives of column debottlenecking include (1) the internal tray modification and (2) the random packing replacing. From simulating, the first alternative is less expanding capacity than the second, and can be only applied to Debutanizer and diesel stripper column. In higher bottlenecks (at least 94 %flooding), the packing replacement is used. Debottlenecking columns have the percent flooding about 80% for packings and 85% for trays which correspond with the recommended range (80 - 85%flooding) [12], shown in Table 7.8 and Figure 7.3.

Table 7.8 Column debottleneck by packing replacement

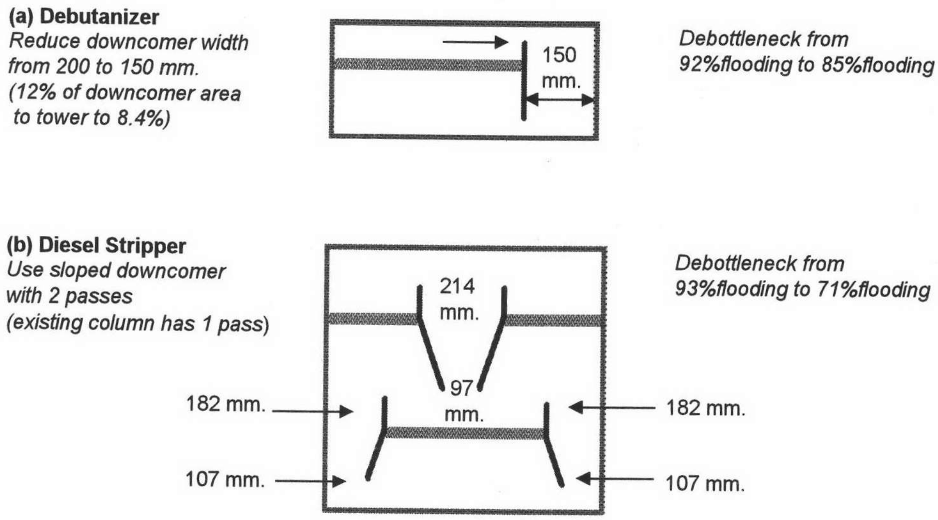
(a) 50 KBD for all cases (A, B, and C)

Unit	Tray No.	Packing Specification Type, material (packing factor, ft^{-1})	Packing Height (m.)	Max. % Flooding
HP fractionator				
	2 - 7	2 inch IMTP, metal (18)	4.1	81
	8 - 9	3 inch IMTP, metal (12)	1.9	75
	10 - 16	2 inch IMTP, metal (18)	4.9	79
	19 - 20	2 inch IMTP, metal (18)	1.4	71
ATM fractionator				
	2 - 6	2 inch IMTP, metal (18)	3.5	74

(b) 60 KBD for all cases (A, B, and C)

Unit	Tray No.	Packing Specification Type, material (packing factor, ft^{-1})	Packing Height (m.)	Max. % Flooding
HP fractionator				
	2 - 7	2 inch IMTP, metal (12)	5.7	80
	8 - 9	4 inch Cascade Minirings, metal (9.8)	1.8	81
	10 - 20	2 inch IMTP, metal (12)	10.6	77
ATM fractionator				
	2 - 3	3 inch IMTP, metal (12)	1.9	72
	4 - 9	2 inch IMTP, metal (18)	4.2	76

Figure 7.3 Debottleneck by internal tray modification for 60 KBD



The random packings are chosen to replace the bottleneck trays because most liquid rates in bottleneck columns(20-40 GPM/ft^2) are higher than the recommended liquid rate of structured packings (less than 20 GPM/ft^2[12]). In addition, the random packing size (or diameter) must be considered. It relies on column pressure drop or hydraulic problems--small packings handle less incremental capacity than large packings because they have higher pressure drop. Therefore, the pumparound (column internal reflux) section--which has the high liquid rate--usually used larger packings than other section. For instance, the pumparound section of HP column (tray 8, 9) uses 3 inch in diameter for 50 KBD and 4 inch for 60 KBD, while other sections use 2 inch for 50 KBD and 3 or 2 inch for 60 KBD. For these material, the metal packings are chosen because they can avoid corrosion and fragility. Moreover, the rising column weight from packing replacement must be considered. It is resulted from two causes :

1. Packing weight is shown in Table 7.9.
2. Column expanding in height is required to obtain the packing supports and distributors or redistributors (about 2 - 3 ft for each packing section), shown in column 4 of Table 7.10.

Table 7.9 Packing weight.

(a) 50 KBD for all cases (A, B, and C)

Unit	Tray No.	Diameter (m.)	Height (m.)	Volume (m3)	Bulk density (kg/m3)*	Weight (kg)
HP fractionator						
	2 - 7	2.74	4.11	24.23	181.03	4,387
	8 - 9	3.35	1.91	16.83	181.03	3,048
	10 - 16	3.35	4.88	43.01	181.03	7,786
	19 - 20	3.35	1.40	12.34	181.03	2,234
Total			12.30	96.42		**17,455**
ATM fractionator						
	2 - 6	2.00	3.50	11.00	181.03	**1,990**

(b) 60 KBD for all cases (A, B, and C)

Unit	Tray No.	Diameter (m.)	Height (m.)	Volume (m3)	Bulk density (kg/m3)*	Weight (kg)
HP fractionator						
	2 - 7	2.74	5.67	33.43	181.03	6,052
	8 - 9	3.35	1.78	15.69	181.03	2,840
	10 - 20	3.35	10.60	93.43	181.03	16,913
Total			18.05	142.55		**25,806**
ATM fractionator						
	2 - 3	2.00	1.94	6.09	181.03	1,103
	4 - 9	2.00	4.25	13.35	181.03	2,417
Total			6.19	19.45		**3,520**

* based on 2 inch of IMTP Packing (11.3 lb./ft^3)[32]

Table 7.10 Total weight of debottlenecking column.

(a) 50 KBD for all cases (A, B, and C)

Unit	Operation Weight (1) (ton)	Packing Weight (2) (ton)	Expanding Column (3) (ton)	Total Weight (1) + (2) + (3) (ton)	Tested Full Water Weight (ton)	% of Total Weight to Full Water
HP fractionator	137.0	17.4	3.3**	157.7	304	51.9
ATM fractionator	74.5	2.0	-	76.5	127	60.2

(b) 60 KBD for all cases (A, B, and C)

Unit	Operation Weight (1) (ton)	Packing Weight (2) (ton)	Expanding Column (3) (ton)	Total Weight (1) + (2) + (3) (ton)	Tested Full Water Weight (ton)	% of Total Weight to Full Water
HP fractionator	137.0	25.8	14.3***	177.1	304	58.3
ATM fractionator	74.5	3.5	-	78.0	127	61.4

Note :

Basis : HP fractionator weight per height is roughly estimated from the total weight divided by total height = 55 ton/27m. = 2.04 ton/m.

** At 50 KBD, the required expanding height of HP fractionator equals 1.6 m. Thus, the expanding-column weight equals 1.6 x 2.04 = 3.3 ton

*** At 60 KBD, the required expanding height of HP fractionator equals 7.0 m. Thus, the expanding-column weight equals 7.0 x 2.04 = 14.3 ton

In Table 7.10, the total weight of debottlenecking columns ranges 50% to 60% of the column weight tested with full water. Thus,the existing column foundation can be support the rising weight of packing replacement.

HEN debottlenecking

HEN debottlenecking is the second task. The existing HEN is debottlenecked by using the pinch analysis with two constraints;

1. Use all existing heat exchangers
2. Avoid to split a stream more than two branches for easy flow controlling.

In pinch analysis, the minimum temperature difference (ΔT_{min}) of HEN must be identified first. The existing ΔT_{min} at 40 KBD is used to redesign the new HEN at 50 KBD and 60 KBD because the temperature profile of distillation columns at 40 KBD are similar to the temperature profile at the 50 KBD and 60 KBD. ΔT_{min} at 40 KBD equals 12°C. When ΔT_{min} and hot and cold streams from separation section are known, the existing HEN can be redesigned for debottlenecking. To debottleneck it in each capacity (50 or 60 KBD), the maximum bottleneck case (of case A, B, and C) is chosen. It requires the maximum duty to heat crude feed, implying the maximum bottlenecks in heat recovery. For this work, the case A is chosen to redesign because it requires the maximum duty as shown in Table 7.11.

Table 7.11 Required duty to heat a crude feed to its flash point

Case	50 KBD	60 KBD
A	**78.7**	**94.5**
B	67.4	80.8
C	77.6	93.1

After the HEN of case A has been debottlenecked, the new HEN of case A must be adjusted by case B and C to guarantee that it can handle for heat recovery of all cases (or any feeds--light, middle, and heavy crudes).

HEN design starts at the pinch, and moves away from the pinch. At pinch matches, the pinch design must be validated two criterions (the stream number and CP inequalities described in Chapter 4), usually requiring stream splitting. Away from the pinch, HEN design is free. Stream splitting is usually required to reduced high pressure drop in tube side of a heat exchanger. In fact, the feasible matches of HEN are many solutions but they requires the special HEN simulators. For this work, the feasible match is design by hand, and then it is examined by rating in PRO/II. Results of HEN debottlenecking shown in Figure 7.4. From these results, the new heat exchangers must be added. Their areas are shown in the percentage of them to the existing areas; for example, 20% area increase at 50 KBD, and 50% area increase at 60 KBD. These areas depend on heat recovery rising with capacity. Thus, their percentages being similar to the incremental capacity percentages (25% for 50 KBD and 50% for 60 KBD) are reasonable.

Utility debottlenecking

Utility debottlenecking is the final task. The utilities include heaters (or furnaces) and coolers.

1. For the heater problem, heater duty is inadequate to heat a crude feed to flash point. To overcome this problem, the new heater must be added in parallel connection with the existing unit. In each capacity (50 or 60 KBD), its duty equates the maximum required duty (of three cases) divided by 80% efficiency of a new heater (shown in Figure 7.5).
2. For the cooler problem, both of heat transfer area and pressure are usually bottlenecks. To solve them, the new unit must be added with parallel connection -- which must split a stream into branches to add new units, and to decrease pressure drop per a stream. Figure 7.5 shows the cooler debottlenecking.

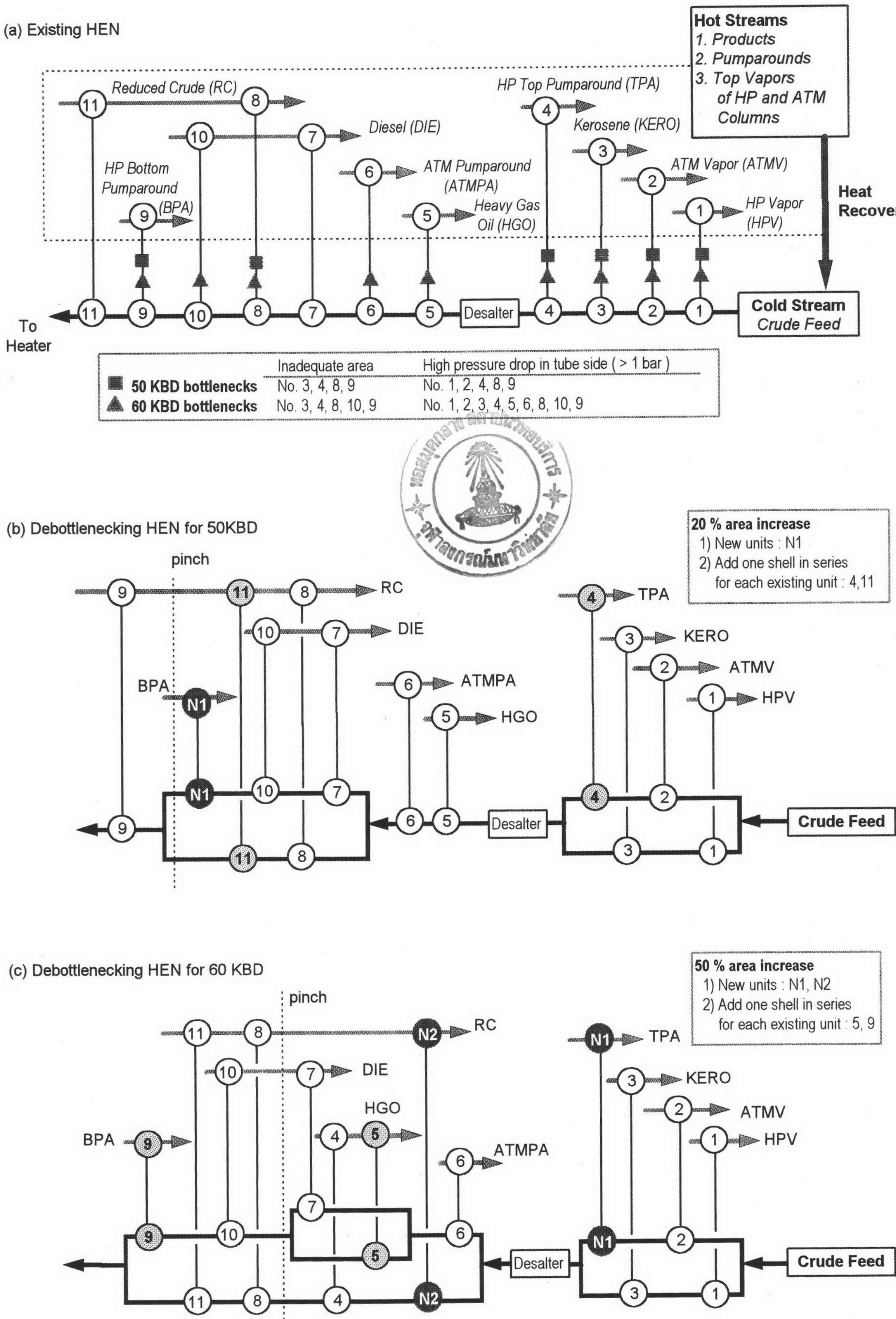


Figure 7.4 HEN debottlenecking

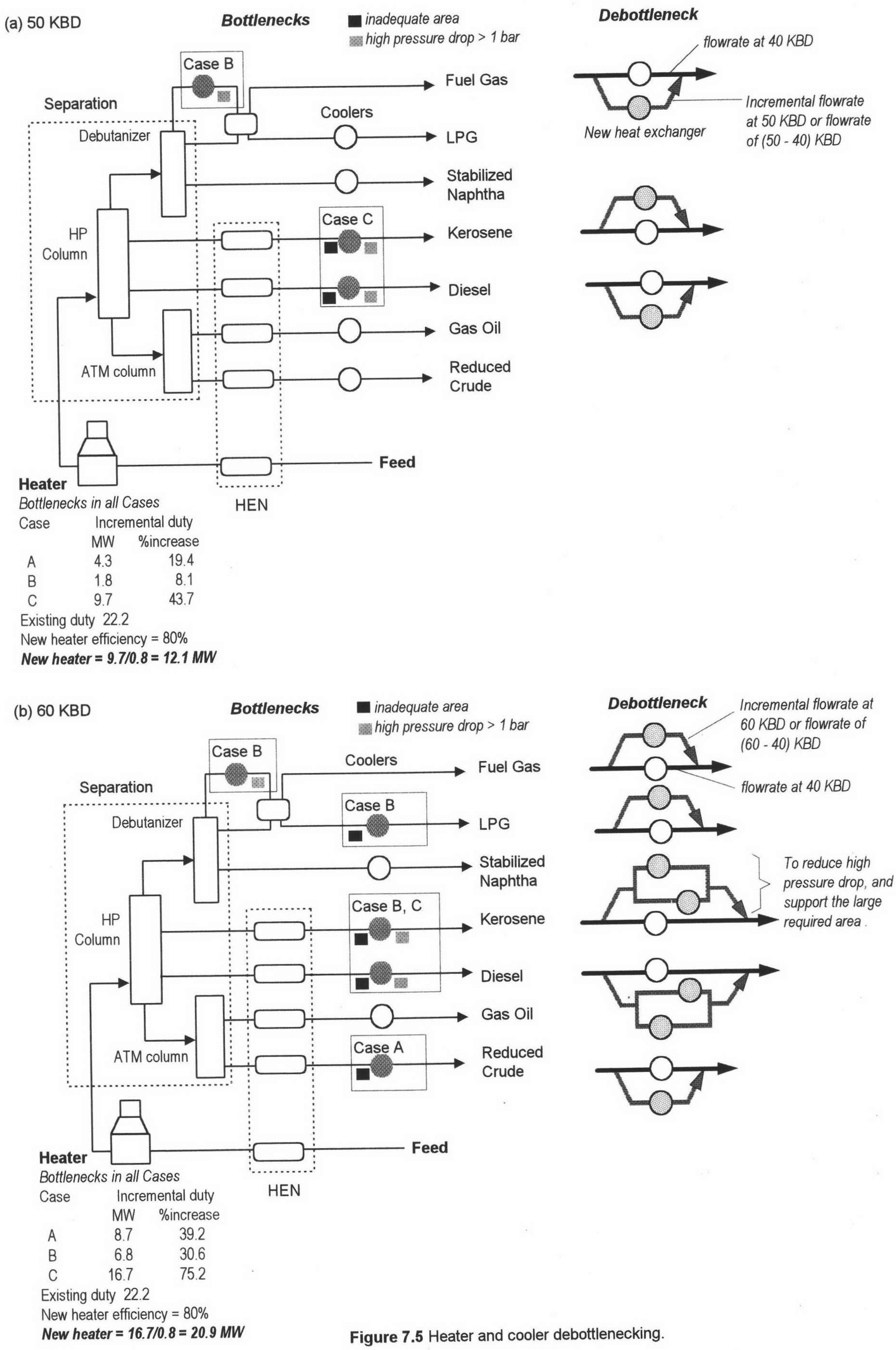


Figure 7.5 Heater and cooler debottlenecking.

Economic Evaluation of Debottlenecking.

The economic evaluation of the debottlenecking is shown in Table 7.12. The economic indexes shows that the debottlenecking of both capacities are suitable to invest because of high rate of return and high net present value. In addition, the payback period of this debottlenecking averages about 2 years corresponding with the published data which ranges 6 month to 2 years [33,34]. For sensitivity analysis shown in Table 7.13, when the capital investment (column) and the gross marginal (row) vary, the debottlnecking profits are still the benefit project. For the minimum profit case, the gross margin decreases 15% when the capital cost increases 15%, the debottlenecking is still a benefit project because of high %IRR and positive NPV. Detail of cash flows are shown in Appendix.

Table 7.12 Economic evaluation of debottlenecking

Basis

- Project life equals 15 years.
- Operating days per year equals 340 days.
- Gross margin estimates 2.7 $/BBL.
- Marginal expense(mainly, utilities) estimates 0.5 $/BBL with 4 % inflation/year.
- Capital cost estimation are based on published data.
- Depreciation is calculated by straight-line method.
- Income tax equals 35% of gross earnings.
- Economic evaluation are based on the incremental capital cost and the incremental capacity.

	50 KBD	60 KBD
Total capital cost (M$)	9.28	16.86
Payback period (year)	2.1	1.9
NPV (discount rate = 15%) (M$)	13.4	28.7
%IRR	47	52

Table 7.13 Sensitivity analysis

(a) 50 KBD

Sensitivity analysis	**Total Capital Cost (M$)**		
	7.9 (down = -15%)	9.3 M$	10.7 M$ (up = +15%)
Gross Margin ($/BBL) 2.3 $/BBL (down = -15%)	Pay back = 2.2 years NPV = 10 M$ %IRR = 44%	2.6 9 37%	3.1 7 31%
2.7 $/BBL	2.2 15 56%	2.1 13 47%	2.4 12 40%
3.1 $/BBL (up = +15%)	2.5 19 68%	2.3 18 57%	2.0 16 49%

(b) 60 KBD

Sensitivity analysis	**Total Capital Cost (M$)**		
	14.3 (down = -15%)	16.9 M$	19.4 M$ (up = +15%)
Gross Margin ($/BBL) 2.3 $/BBL (down = -15%)	Pay back = 2.0 years NPV = 22 M$ %IRR = 50%	2.4 20 41%	2.8 17 35%
2.7 $/BBL	1.6 31 62%	1.9 29 52%	2.2 26 45%
3.1 $/BBL (up = +15%)	1.3 41 75%	1.6 38 63%	1.8 35 54%