Solutions for R&D to Design

Guidelines for Distillation Column Thermal Analysis and Optimal Reflux Ratio

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PreFEED Corporation

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Distillation Column Thermal Analysis Process Improvement Proposal Investigation

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Process Improvement Proposal Investigation

- For an existing distillation column, various conditions including the feed composition may be changed from the time it was designed, so there is a possibility that a large energy loss may occur even if the distillation column specs are met in the current operation.
- The method for determining the distillation column specs using the relationship between the minimum reflux ratio and the number of theoretical stages (optimum reflux ratio) is effective and is currently most commonly used, but it is difficult to simultaneously examine the possibility of changing the feed stream conditions and of reducing energy losses in the column by side heat exchangers.
- In the process improvement plan examination using the column target method, it is possible to visually judge the required energy level and the room for improvement of energy loss.
- Here, we will aim to study a process improvement plan from the viewpoint of energy using the column target method.

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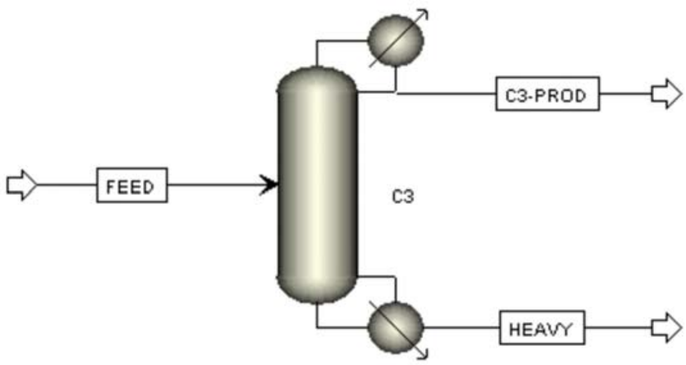
Depropanizer Column

- In a LPG refinery process, column targeting is applied to an existing distillation column that separates propane from a mixture leaving a deethanizer
- Spec.: Purity of propane and lower boiling point components : 99 mol%, Propane recovery rate : 98%
- Number of theoretical stages : 16, feed stage : 6, column pressure : 18 atm

Feed flow rate 100 kmol/h, Pressure 20 atm, Temperature 40C

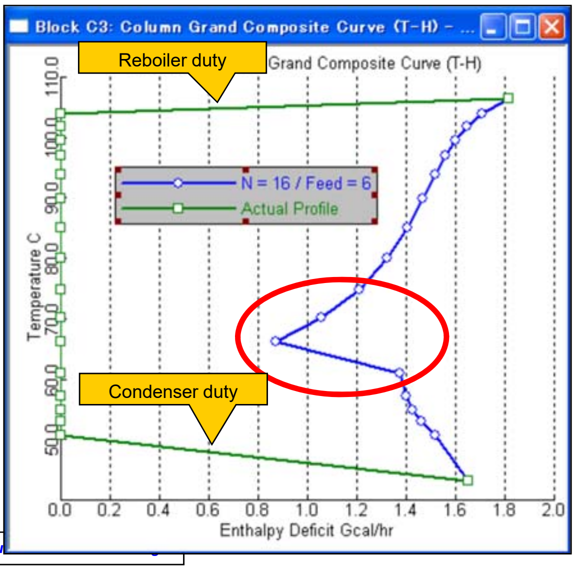
Feed composition (in mol%):

Methane	: 0.005
Ethane	: 0.020
Propane	: 0.400
Iso-butane	: 0.200
N-butane	: 0.320
N-pentane	: 0.055



Column Targeting Results

- In the CGCC (Column Grand Composite Curve) diagram, the blue line represents the ideal profile for a finite number of stages, the green lines represent the actual reboiler (upper line) and the condenser (lower line), and the area surrounded by each line indicates the possibilities of heat recovery.
- Since the feed is not properly placed, a large distortion can be seen above the feed stage (in the rectifying section).

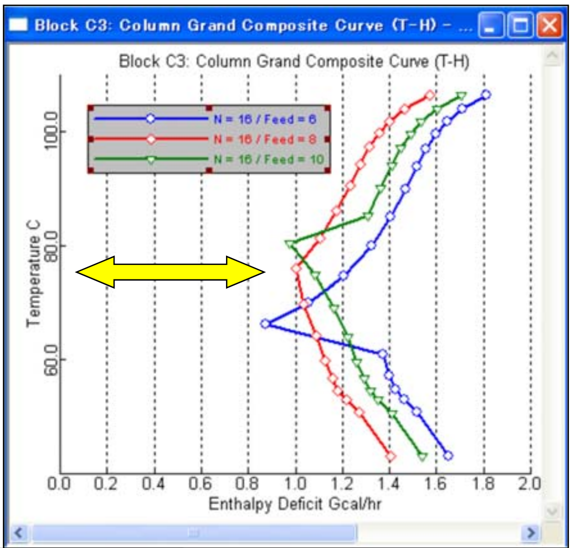


	Existing Column
Number of Theoretical Stages	16
Feed Stage	6
Reflux ratio	11.5
Reboiler duty (MMkcal/hr)	1.81
Condenser duty (MMkcal/hr)	1.65
Approximate Column Diameter (mm) – Sieve tray	1100

- Since the number of rectifying section stages is insufficient, we will examine the impact of lowering the feed stage.

Column Targeting - Impact of Feed Stage

- The feed stage is moved from Stage 6 to Stage 10. A heat recovery possibility of about 13% can be expected by optimizing the feed position. If the feed is lowered to Stage 10, it can be seen that the number of recovery stages required for separation becomes insufficient.
- On the other hand, an energy loss of about 1 MMkcal/h occurs even when the feed is at Stage 8.

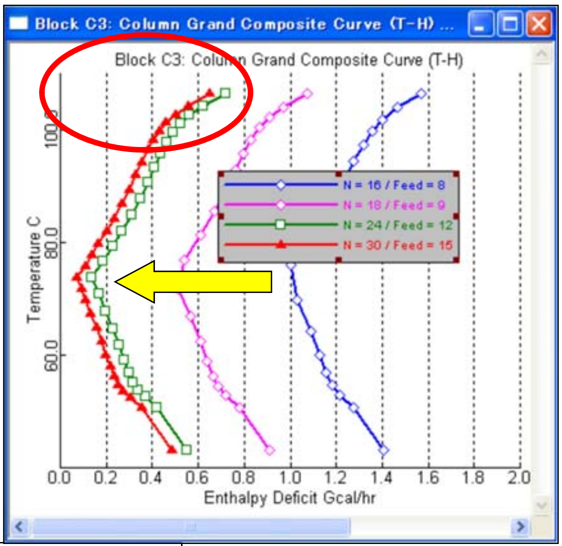


	Existing Column	Feed Position
Number of Theoretical Stages	16	16
Feed Stage	6	8
Reflux ratio	11.5	9.69 (-15.7%)
Reboiler duty (MMkcal/hr)	1.81	1.57 (-13.3%)
Condenser duty (MMkcal/hr)	1.65	1.40 (-15.1%)
Approximate Column Diameter (mm) – Sieve tray	1100	1050 (-4.5%)

- Next, we will examine the impact on the results of increasing the number of theoretical stages.

Column Targeting - Impact of Number of Theoretical Stages

- The number of theoretical stages is changed from 16 to 30. Nearly 70% of heat recovery can be expected by increasing the number of theoretical stages in addition to the optimizing the feed stage position.
- On the other hand, even if the number of stages is increased beyond 30 stages, it can be seen that it is unlikely to expect any further significant heat recovery.

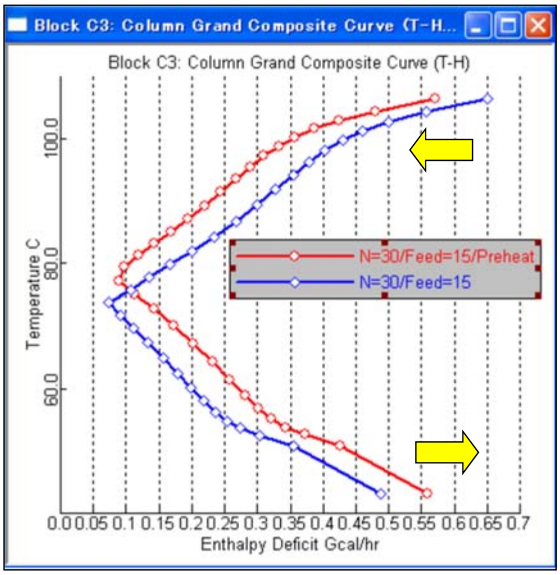


	Existing Column	Number of Theoretical Stages
Number of Theoretical Stages	16	30
Feed Stage	6	15
Reflux ratio	11.5	2.71 (-76.4%)
Reboiler duty (MMkcal/hr)	1.81	0.65 (-64.1%)
Condenser duty (MMkcal/hr)	1.65	0.49 (-70.3%)
Approximate Column Diameter (mm) – Sieve tray	1100	800 (-27.3%)

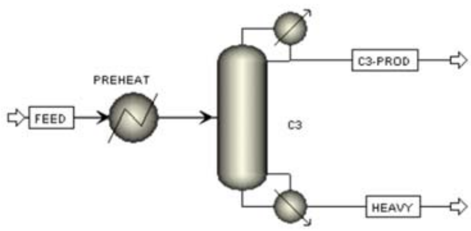
- Next, we will consider improving the reboiler heat recovery by preheating the feed.

Column Targeting - Impact of Feed Conditions

- The feed stream temperature is increased from 40C to the saturated liquid temperature (80.7C). As a result, it may be possible to further reduce the reboiler duty (0.1 MMkcal/h), but conversely the condenser load increases. Also, as new equipment such as a preheater would be required, it can be concluded this case has little merit.



	Existing Column	Preheat
Number of Theoretical Stages	16	30
Feed Stage	6	15
Reflux ratio	11.5	3.24 (-71.8%)
Reboiler duty (MMkcal/hr)	1.81	0.57 (-68.5%)
Condenser duty (MMkcal/hr)	1.65	0.56 (-66.1%)
Approximate Column Diameter (mm) – Sieve tray	1100	800 (-27.3%)



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	Existing Column	Feed Position	Number of Theoretical Stages	Preheat
Number of Theoretical Stages	16	16	30	30
Feed Stage	6	8	15	15
Reflux ratio	11.5	9.69 (-15.7%)	2.71 (-76.4%)	3.24 (-71.8%)
Reboiler duty (MMkcal/hr)	1.81	1.57 (-13.3%)	0.65 (-64.1%)	0.57 (-68.5%)
Condenser duty (MMkcal/hr)	1.65	1.40 (-15.1%)	0.49 (-70.3%)	0.56 (-66.1%)
Approximate Column Diameter (mm) – Sieve tray	1100	1050 (-4.5%)	800 (-27.3%)	800 (-27.3%)
Relative Energy Cost Comparison (Existing Column Basis)	100%	87%	36%	31%
Relative Distillation Column Cost Comparison (Existing Column Basis)	100%	97%	192%	192%

- The cost impact greatly changes depending on utility costs and equipment material. It can be seen that the possibility of energy reduction can be visually confirmed by the column targeting (on the existing column basis).
- In this study, the relative cost of the main distillation column was mentioned as a reference value, but of course in the case where preheaters and side heat exchangers are considered, since the reboiler and condenser costs will change due to load changes, it is necessary to check these costs together.

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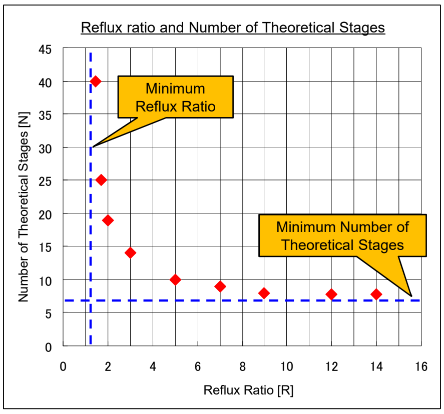
Examination of Optimum Reflux Ratio

Examination of Optimum Reflux Ratio

- Increasing the reflux ratio will increase the load in the column and increase the column diameter, and decreasing the reflux ratio will increase the number of theoretical stages and increase the column height. That is, when studying the distillation column, it is necessary to decide on an optimal reflux ratio by considering construction costs and operation costs.
- In general, the optimum reflux ratio is often considered to be around 1.5 times the minimum reflux ratio, but recommended values vary depending on references in the literature.
- Accordingly, we will aim to examine the optimal reflux ratio using the column targeting method *).



Note). For details about the concepts of the column targeting method and the CGCC creation method, refer to "Distillation Column Thermal Analysis - Column Targeting Method" (Tips #0906).

Examination of Optimal Reflux Ratio

- By considering the total cost, that is, the sum of the fixed costs and the operating costs, the minimum value at a certain reflux ratio can be found. At this time, R is called the optimal reflux ratio and is usually expressed as Ropt. Experience indicates that the optimal reflux ratio (Ropt) is in a range of approximately 1.2 to 1.5 times the minimum reflux ratio (Rm). However, in actual design, the reflux ratio is usually set slightly larger than Ropt. This is better because it allows more flexibility for the equipment. Therefore, the optimum reflux ratio from a design perspective usually has the following value.
  Optimal Reflux Ratio: R = 1.5~2.0 x Rm
  "Jouryu no Riron to Keisan (in Japanese)"
- Increasing the reflux ratio decreases the number of theoretical stages, but accordingly, the steam flow rate in the column increases and the heat duties of the total condenser and the reboiler increase. Therefore, there is an optimum value (Ropt) for the reflux ratio. Usually, the optimal reflux ratio (Ropt) is in the range of the following equation.
  Ropt / Rm = 1.05~1.2
  "Kagaku Kougaku Binran, Revised 6th ed. (in Japanese)"

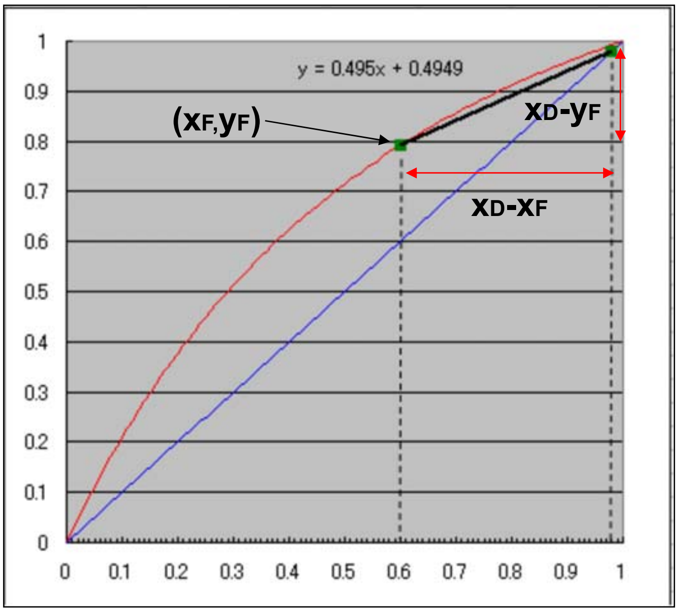
A mixture of 60 mol% benzene and 40 mol% toluene, fed at 100 kmol/h and at 1 atm is to be separated by distillation to obtain 98 mol% benzene at the top and 95 mol% toluene at the bottom of the column.
Assuming the feed is a saturated liquid, we will find the minimum reflux ratio and examine Ropt.

	Case1	Case2	Case3
Ropt/Rm	1.05	1.5	2.0

In a binary system, the minimum reflux ratio (R_m) can be obtained from the point where the rectifying section operating line and the *x-y* curve intersect in the feed supply condition. Assuming that the distillate composition is x_D and the intersection of the operating line and the vapor-liquid equilibrium line is (x_F, y_F), the following equations hold.

$$\frac{R_m}{(R_m+1)} = \frac{(x_D - y_F)}{(x_D - x_F)}$$

$$R_m = \frac{(x_D - y_F)}{(y_F - x_F)}$$



The feed is, from the saturated liquid, q = 1 (x_F =0.6), x_D = 0.98, x_B = 0.05

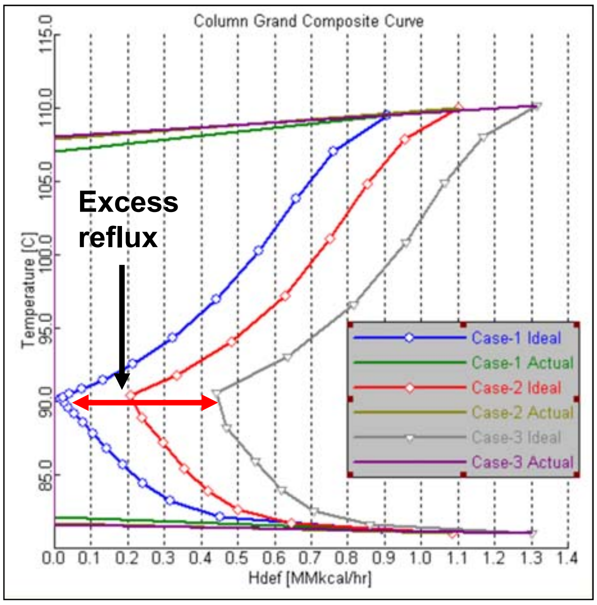
Operating line slope =0.495, R_m = 0.98

Optimum Reflux Ratio – Investigation Results

- From the column target analysis result, Case 1 seems to represent a condition close to the ideal relation between reflux and the number of stages. In Case 3, the amount of heat loss generated in the column is large, but the theoretical plate number is small. (The heat loss is close to 45% larger compared to Case 1)

- From the viewpoint of energy, Case 3 seems to be more advantageous than Case 1 regarding the cost of the distillation column. Therefore, we have performed a rigorous simulation using Aspen Plus to check the separation performance and compare the approximate costs.

	Case1	Case2	Case3
Ropt/Rm	1.05	1.5	2.0
Ropt	1.029	1.47	1.96



Optimum Reflux Ratio – Rigorous Simulation Results

	Case 1	Case 2	Case 3
Ropt/Rm	1.05	1.5	2.0
Number of Theoretical Stages (MacCabe-Thiele)	21	13	11
Feed Stage (MacCabe-Thiele)	12	7	6
Top BZ Concentration (Rigorous Simulation)	0.971	0.980	0.982
Reboiler duty (MMkcal/hr)	0.91 (100%)	1.1 (121%)	1.32 (145%)
Approximate Column Diameter (mm) – Sieve tray	1000	1100	1200
Relative Cost Comparison (Case1 Base Estimate)	100%	79%	78%

- In Case 1, it can be seen that the BZ concentration Spec is not satisfied (even with 100 theoretical stages it can only be separated up to 97.7 mol%).
- The temperature at the bottom of the column is around 110C and the effect of the utility unit cost is not very large, but Case 2 is about 20% more thermally advantageous than Case 3.
- Considering the total cost, Case 2 (1.5 times Rmin) is the most advantageous in this study.

Conclusion

- As a guideline for the optimal reflux ratio, it is reasonable to set it at approximately 1.5 times the minimum reflux ratio.
- By using the column target method, it becomes possible to carry out an optimization study of a distillation column from the standpoint of energy (feed conditions, feed stage position, reflux vs. number of theoretical stages, side heat exchanges). On the other hand, caution is required because it is possible that the investigation results become unrealistic unless operating costs and fixed costs are taken into consideration for everything around the distillation column.