내부 열교환 증류탑의 설계와 성능해석

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Design and Performance Analysis of Internally Heat-Integrated Distillation Columns (HIDiCs)

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INTRODUCTION

Distillation is a separation process using lots of energy as the separation medium [1], and therefore its energy efficiency has been a major target in the study of its improvement. An obvious solution is the heat integration between its condenser and reboiler, though they can not be integrated directly for the heat recovery due to their unfavorable temperature difference. The reboiler temperature is higher than that of the condenser. A vapor compression or vacuum is applied to reverse the temperature difference and to make the heat recovery available. For the improved heat recovery, the internally heat-integrated distillation column (HIDiC)[2] modifies the temperature distribution by increasing the pressure of the whole rectifying section of the distillation column instead of the condenser in the direct heat integration [3].

In the studies of the internally heat-integrated distillation (HIDiC), no commercial software of distillation column design provides a ready-use heat-integrated column in the development of process flow diagram. Instead many external heat exchangers are used for the tray-by-tray heat transfers along with artificial streams from the trays, which require lots of stream information leading to the convergence problem in the process simulation of the HIDiC. In this study an approximate design and simulation procedure with simple computation is proposed, and its performance is examined with two commonly used processes in the studies of the HIDiC design and cost evaluation.

DESIGN PROCEDURE

The conceptual structure of the internally heat-integrated distillation column is shown in Figure 1. In a conventional distillation column the temperature of the rectifying section is lower than that of the stripping section, and therefore the tray-by-tray heat transfer demonstrated in the figure is not available. The vapor compression raises the temperature in the rectifying section, and the heat released from the rectifying section is recovered and supplied to the stripping section.

The material balance at a tray is given as

$$V_{j+1}y_{j+1} + L_{j-1}x_{j-1} - V_j y_j - L_j x_j + \delta_F\, q\, F\, x_F = 0 \tag{1}$$

where the subscript j indicates tray number and counted from the top, and the feed is supplied only at the feed tray. Because the system is binary, no component indication is necessary. The feed quality q is determined from the flow rate of top product. The vapor and liquid flow rates are

$$V_j = V_{j+1} + \frac{Q_j}{\lambda_j} \quad \text{and} \quad L_j = L_{j-1} - \frac{Q_j}{\lambda_j} \qquad (2)$$

where Q_j is the amount of the transferred heat and λ_j is the heat of vaporization. The vapor-liquid equilibrium is formulated as

$$y_j = K_j x_j \qquad (4)$$

For the simplicity the relative volatility is used here to replace the equilibrium constant.

$$y_j = \frac{\alpha}{1+(\alpha-1)x_j} x_j \qquad (5)$$

The set of material balances is transformed to the matrix form, and an iterative procedure using a relaxation factor is applied to calculate the liquid composition.

$$AX=C \qquad (6)$$

EXAMPLE PROCESSES

Two widely used processes in the HIDiC studies are employed in the evaluation of the proposed design procedures of this study. The benzene-toluene process [4] has been examined from the early studies in the field. The vapor-liquid equilibrium is close to ideal and their boiling points are relatively wide resulting in easy separation. Two different relative volatilities are used here for the rectifying and stripping sections. All the trays of rectifying and stripping sections are involved in the heat transfer. The second process is a close boiling system of propylene- propane process. Because the tight separation requires lots of energy demand in the conventional distillation system, many studies have been conducted to find an energy efficient process for the separation. Due to the feed condition the tray number of stripping section is less than the rectifying section, and the top of the rectifying section is paired in the heat transfer. The detail of column structures and operating conditions is listed in Table 1. The column structure and operating conditions are summarized for either of the HIDiC and conventional distillation systems. In the HIDiC the rectifying section is operated at the elevated pressure to give sufficient temperature difference for the heat recovery, and the different relative volatilities are used for the rectifying and stripping sections. For the fair comparison the HIDiC and conventional distillation systems are under similar conditions.

RESULTS AND DISCUSSION

The internally heat-integrated distillation column (HIDiC) has been introduced for the heat recovery from the rectifying section by raising its operating pressure to have the tray-by-tray heat transfer to the stripping section. Therefore neither condenser nor reboiler is necessary in the ideal HIDiC. In practice, a small size condenser and reboiler are installed for the startup of the distillation column. Figure 2 shows the schematic diagram of the practical HIDiC. In case of benzene toluene system the tray numbers of the rectifying and stripping sections are the same, and the tray-by-tray pairing is given from the top to the bottom of both sections. However, the propylene-propane system has different tray numbers as given in Table 1. The design of the conventional distillation column used for the performance comparison utilized the same procedure with no in-tray heat transfer. The optimum number of trays is found from the comparison of the total annual cost as plotted in Figure 3. The tray numbers of 50 and 270 for the benzene-toluene and propylene-propane systems, respectively, are determined from the figure.

The computation of vapor-liquid equilibrium is approximated with using the relative volatility in this study of the approximate design, but the equilibrium of the systems used here is close to the ideal and the approximation does not leave a large computational error. Figure 4 demonstrated the difference between the rigorous and approximate computations, which does not show noticeable discrepancy. The circles are from the experimental data and the rigorous VLE computation, and the curve is calculated from the relative volatility.

The cost of utilities is very critical to determine the economic comparison of the total annual cost for the HIDiC and conventional columns. The investment cost is counted with the 10 year payback. In the vestment cost of the compressor takes a large portion in both processes, and the steam and electricity costs are the main in the utility cost. While the cost comparison in the benzene-toluene process gives a mild improvement of 8.1 % in the HIDiC, that in the propylene-propane process does a large improvement of 59.3 %. Because the process is a close boiling point process requiring a large amount of tray numbers and steam consumption, the steam cost has a significant role in the cost comparison. Therefore the HIDiC is more useful in the tight separation processes.

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Table 1. Structural information, operating conditions and compositions in the proposed and conventional distillation systems. Tray numbers are counted from the top.

Name		Benzene-toluene HIDiC (Rectifying/Stripping)	Benzene-toluene Conv.	Propylene-propane HIDiC (Rectifying/Stripping)	Propylene-propane Conv.
Structural(Number of trays)					
Total		**64**	**50**	**270**	**270**
Rectifying/Stripping		**32/32**	**25/25**	**150/120**	**150/120**
Heat transfer area in tray (m^2)		**20**		**400**	
Overall heat transfer coeff. (W/m^2K)		**600**		**1000**	
Operating	**Pressure (kg/cm^2)**	**2.55/1.0**	**1.0**	**14.6/11.2**	**11.2**
	Relative volatility	**2.06/2.35**	**2.35**	**1.13/1.15**	**1.15**
	Feed (kmol/h)	**300**	**300**	**2601.6**	**2601.6**
	Feed quality	**0.5**	**0.5**	**0.52**	**0.52**
Composition (mol frac.)	**Feed**	**0.5/0.5**	**0.5/0.5**	**0.52/0.48**	**0.52/0.48**
	Product-overhead	**0.995**	**0.995**	**0.995**	**0.995**

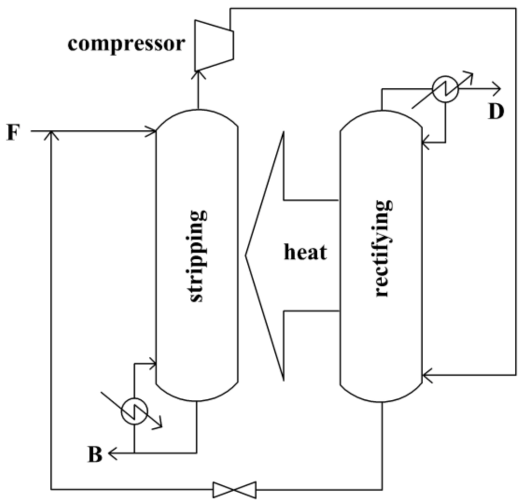

Figure 1. A conceptual diagram of the internally heat-integrated distillation column (HIDiC).

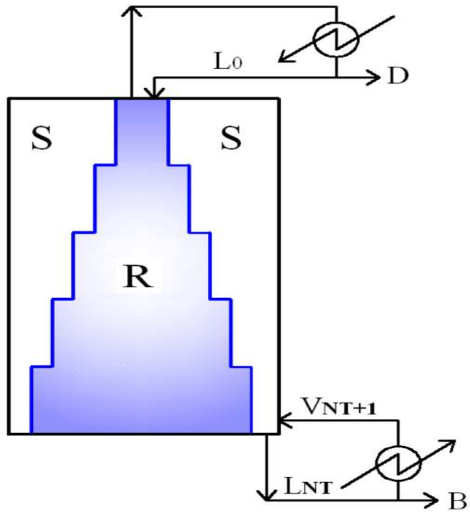

Figure 2. A schematic diagram of the internally heat-integrated distillation column (HIDiC). The symbol S indicates the stripping section, and R does the rectifying section.

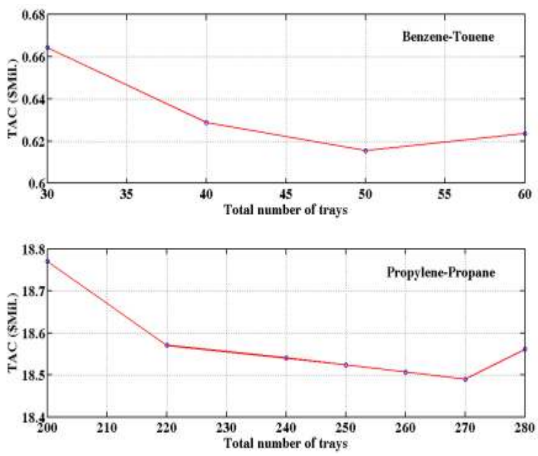

Figure 3. A search of the tray numbers having the minimum total annual cost calculated using the approximate design procedure in the conventional distillation columns.

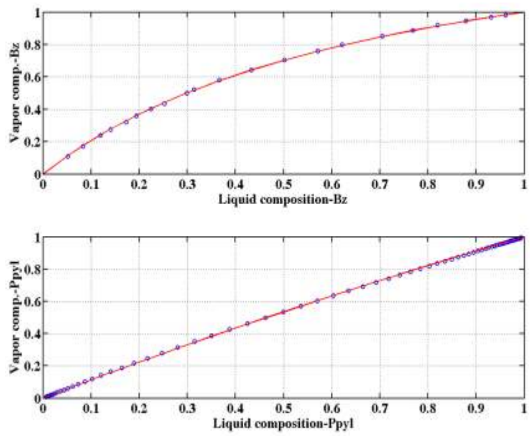

Figure 4. A comparison of vapor-liquid equilibrium computed from the rigorous (circles) and approximate (curve) equations. Top is the system of benzene-toluene, and bottom is of propylene-propane.