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A Partially Heat Integrated Ternary Distillation Column

Bandaru Kiran, Amiya K. Jana* and Amar Nath Samanta

Department of Chemical Engineering, Indian Institute of Technology−Kharagpur,
West Bengal-721 302, India

Abstract. In this work, a ternary distillation column is used for internal thermal coupling. The influence of the partially heat integrated ternary distillation column (HITDC) on the energetic aspects is evaluated through intensive comparison against the conventional standalone column. The simulated column has been used for finding the quasi-optimal values of the design and operating parameters. It is observed that the HITDC system appears superior to its conventional counterpart providing about energy savings of 59.9%.

Keywords: Partial HITDC, simulation, parametric sensitivity, energy savings

1. Introduction

There is no doubt that distillation is the most mature and widely used separation process in the chemical and process industries. However, it uses huge amounts of energy with a rather inefficiency. It is reported[1] that nearly 4% of the total energy requirement in the USA in 1988 is directed to distillation processes. In the distillation operation, conventionally the thermal energy is added at the reboiler and thrown away at the condenser. To improve the energy efficiency of the distillation columns, several heat integrated distillation columns (HIDiCs)[2,3] have been developed.

It is true that the degree of heat integration and controllability are likely to have an inverse relation. It is observed[4] that for the case of highly energy efficient HIDiC, i.e. intensified ideal HIDiC, there is a pole lie at the origin of the complex plane, and hence the complexities in process operation and control arise. It is not expected that one would build a highly energy efficient process that is very poorly controllable or even uncontrollable. Recently, Ho et al.[5] have analyzed an ideal HIDiC, a HIDiC with a pre-heater and a HIDiC with a reboiler by control degrees of freedom (DOF). From thermodynamic and DOF analyses together with the engineering judgment, they have shown that a reboiler is necessary for the HIDiC in practice. Motivated by these facts, the present work aims to deal with a partially HIDiC that includes both reboiler and condenser.

The present work explores the feasibility of internal heat integration on a ternary distillation column. Several simulation experiments have been performed for detailed analysis. Parametric sensitivity tests have been conducted on the simulated column for finding the values of the design and operating parameters. It is observed that the HITDC provides an energy savings of 59.9%.

2. Process Description

2.1. Conventional column

For heat integration, a distillation process is exampled that fractionates a ternary mixture of propane, *n*-butane and *n*-pentane. The column has total 12 stages (excluding total condenser and reboiler). The numbering of stages is started from bottom upward. The feed (saturated liquid) is introduced in Stage 6. The operating parameters and steady state values are detailed in Table 1.

* Corresponding author. Tel.: +91-3222-283918; fax: +91-3222-282250.
E-mail address: akjana@che.iitkgp.ernet.in.

Table1: Process Parameters and Steady State Values.

Items	*CTDC*	*HITDC*
Feed flow rate (lbmol/hr)	500	500
Feed composition (C_3/n-C_4/n-C_5)	0.5/0.3/0.2	0.5/0.3/0.2
Top composition (C_3)	0.9834	0.9834
Bottom composition (C_3)	0.0149	0.01485
Distillate rate (lbmol/hr)	180	180
Bottoms rate (lbmol/hr)	320	320
Reflux ratio	0.66	0.66
Column diameter (ft)	1.865	1.865
Total number of trays	12	6+6
Feed stage	6	6
Stage pressure drop (psi)	0.0725	0.0725
Bottom stage pressure (psia)	221.37	221.37 (stripper)

2.2. Heat integration

The internal heat integration technique has been applied to the conventional ternary distillation column (CTDC) keeping the input and output specifications identical. The target purity level in the top product is set at 98.34 mole%. The HITDC consists of two separate columns (rectifier and stripper). For the adjustment of pressure difference between the rectifying and stripping section, a compressor and a throttling valve are installed. Selected number of internal tray-to-tray heat exchangers can be used for transferring the heat from rectifier to stripper. The trim-reboiler and trim-condenser are required for start-up operation of the HITDC.

In the heat integrated column, the overhead vapor stream of the stripping section is compressed and then introduced at the bottom of the rectifying column. As a result, there exists a pressure difference between the two columns. The bottom liquid of the rectifying section is fed into the top of the stripping section, as is the feed to the stripping column. The pressure of the recycled liquid from the rectifying section is equalized with that of the stripping stage using a throttling valve. Because of the internal thermal coupling, a certain amount of energy is transferred from the rectifier to the stripper and brings the downward reflux flow for the former and the upward vapor flow for the latter. This results in reduction of the reboiler heat load. But at the same time, an additional compressor duty is involved in the thermally coupled column.

In the HITDC scheme, the rectifying section that includes the trim-condenser and the stripping section that combines the trim-reboiler have the same number of stages (i.e., 7 theoretical stages).

Model development

The following assumptions are made in deriving the mathematical model for both the CTDC and HITDC schemes.

- Liquid on the tray is perfectly mixed and incompressible.
- Vapor holdup in the column is negligible.
- Vapor-liquid equilibrium (VLE) is calculated using the Wilson model.[6]
- Tray pressure drop (0.0725 psi) and efficiency (70%) are constant and same for all trays.
- Liquid hydraulics are calculated from the nonlinear Francis weir formula.[6]
- For the heat integrated structure, heat transfer is computed by $UA\Delta T$, where U (Btu/hr.ft^2.^{0}F) denotes the overall heat transfer coefficient, A the heat transfer area (ft^2) and ΔT the temperature difference (^{0}F) between the rectifying tray and stripping tray.

For brevity, the model structure of a distillation column is not reported here and it is available elsewhere.[6] The HITDC additionally includes the following equations:

Internal heat exchanger

$$Q_n = UA\,(T_{((n_t/2)+n)} - T_n) \quad \text{(1a)}$$

Stripping section

$V_n^S = Q_n / \lambda_n$ (1b)

Rectifying section

$L_n^R = Q_n / \lambda_n$ (1c)

Compressor

The following equation has been used to calculate the compressor work (Q_{comp}):

$$Q_{comp} = 1.27 \times 10^{-3} \frac{\mu}{\mu - 1} V \frac{MWA}{DENSA} \left[\left(\frac{P_R}{P_S} \right)^{\frac{\mu-1}{\mu}} - 1 \right] \quad (2)$$

Where, *DENSA* and *MWA* are the average liquid density and molecular weight, respectively. Suffix *R* and *S* have been used, respectively, to represent the rectifier and stripper. The polytropic coefficient (μ) is calculated from:

$$1/(\mu_i - 1) = \sum [y_{n,i} / (\mu_i - 1)] \quad (3)$$

Compression of vapor from the stripping section to the rectifying section:

$$T_{CO} = T_S \left(\frac{P_R}{P_S} \right)^{\frac{\mu-1}{\mu}} \quad (4)$$

Where T_{CO} is the outlet temperature of the compressor (^{0}F). In the above model equations, L denotes the liquid flow rate (lbmol/hr), P the pressure (psia), Q the heat duty (Btu/hr), T the temperature (^{0}F), y the vapor composition (mole fraction), V the vapor flow rate (lbmol/hr), and λ the latent heat (Btu/lbmol).

3. Thermodynamic Feasibility of HITDC

When there is no energy coupling between the rectifying and stripping columns of a HITDC scheme, the reboiler and condenser operate on maximum heat loads. The temperature for each stage in both the columns (stripping and rectifying) with no internal tray-to-tray heat transfer is obtained in Figure 1. In this simulation, total number of stages (n_T) is 12, stage pressure drop (ΔP) is 0.0725 psi, compression ratio (CR) ($= P_R / P_S$) is 2.20, and reflux ratio (RR) is 0.66. Figure 1 indicates that although the temperature driving force varies along the columns, it is always positive between all the rectifying and stripping column stages. When the rectifier is hotter than the stripper, a heat integrated column configuration with respect to design and operation is thermodynamically feasible. Therefore, the sample distillation column is a suitable case for heat integration.

The feasibility regions of energy integration can be determined from the simulated stage temperature profiles. For the HITDC, we consider the typical cut off value of $\Delta T_{\min}$ of ~59^{0}F. Accordingly, it is suggested to install the five internal heat exchangers connected between the rectifying and stripping stages, namely 1−7, 2−8, 3−9, 4−10, and 5−11.

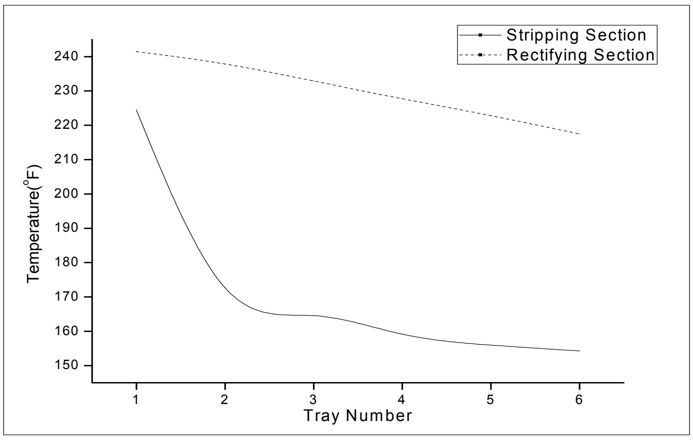

Fig. 1: HITDC stage temperature profiles (in this figure, stage numbering in both the sections is started from bottom up).

4. Conceptual Design of HITDC and Energy Savings

In the present study, a number of sensitivity tests have been carried out in order to tune the design and operating variables. Here, the design variables considered are the total number of stages (n_T) and the product of the overall heat transfer coefficient and the heat exchange area (UA), and the operating variables include the CR and RR. Note that the total number of stages is kept unaltered.

Performing the sensitivity tests for the heat integrated distillation structure, the following quasi-optimal values have been obtained: CR=2.2, n_T =12, RR=0.66, ΔP =0.0725 psi and UA =4.8$\times 10^3$ Btu/hr.^{0}F.stage.

The energy consumption (Q_{cons}) of the heat integrated column is determined by adding the reboiler duty (Q_R) plus three times the compressor duty (Q_{comp}). The overall energy consumptions by the HITDC and its conventional counterpart are obtained as 0.97×10^6 Btu/hr and 2.42×10^6 Btu/hr, respectively. This represents the energy savings (= $[(Q_{CTDC} - Q_{HITDC}) / Q_{CTDC}]\times 100$) of 59.9% by the HITDC.

5. Conclusions

In this paper, the internal thermal coupling has been made in a ternary distillation column. The process simulator has been developed with solving the developed model and then used to find the values of design and operating variables. The final heat integrated structure shows an energy savings of 59.9%.

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