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Dynamic Behavior of an Internally Heat-Integrated Distillation Column (HIDiC)

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This paper reports the analysis of the energy saving for design of an internally heat integrated distillation column (HIDiC) conducted in the second-phase of Japanese national research project for energy conservation in multicomponent petroleum distillation. The practical commercial scale distillation column separating cyclopentane from a multicomponent mixture consisting of mainly C5 hydrocarbons was selected as a target of the application of HIDiC technology. By choosing the compression ratio, the number of the theoretical stages, and the heat transfer rate as design and operating variables, temperature, pressure, flow rates, and composition profiles were computed as well as the reboiler heat duty of the HIDiC by Pro/II. The energy consumption of the HIDiC was compared with that of the practical conventional distillation column operated at the minimal reflux ratio. It was confirmed that at least 25 % of energy saving can be achieved by means of the HIDiC system. A pilot plant of the HIDiC was designed based on the results obtained in this study. It was constructed and has been in operation since 2005. The pilot HIDiC shows more than 50 % of energy savings compared to the conventional distillation column, validating the analysis of this study.

1. Introduction

Distillation is said to be the most mature and frequently used technology of separation processes in many literature on chemical engineering (Keller, 1987; Miyahara, 2004). Adding a large amount of thermal energy as a separating agent, products of chemical processes can be highly purified and fractionated by distillation. In addition, the production rates of a distillation column are usually higher than the other separation instruments. Therefore, the energy consumption of a distillation process is generally much larger than the other separation methods. So far, many modifications of distillation columns have been proposed and utilized in the chemical industries. Among such new developments of distillation processes, an internally Heat-Integrated Distillation Column (HIDiC) is one of the promising alternatives.

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A typical configuration of the conventional distillation column is shown in Figure 1. It consists of the rectifying section, the stripping section, the reboiler and the condenser. If the energy discharged from the condenser (or the rectifying section) were utilized for the energy supplied to the reboiler (or the stripping section), energy saving distillation can be realized with very small heat duty or without any outside heat source. In order to pump up the energy from the condenser to the reboiler, the temperature level of the condenser is needed to be higher than that of the reboiler. One of the systems to realize it is also shown in Figure 1. If the rectifying section is pressurized by a compressor to raise its temperature level, internal heat integration can be expected by contacting the rectifying section with the stripping section. The latent heat released by the partial condensation of the vapor in the rectifying section can be utilized to evaporate the liquid in the stripping section, i.e. the internal reflux. The liquid flow rate increases downward in the rectifying section whereas the vapor flow rate increases upward in the stripping section.

The basic process flow diagram of the HIDiC pilot plant constructed in 2005 is shown in Figure 2. The design specifications were set the same as those of an existing conventional commercial column (pentane column) in order to make a fair comparison with the simulation results (Horiuchi et al., 2009; Nakaiwa et al., 2009).

In this study, we have developed the HIDiC models by the process simulator.

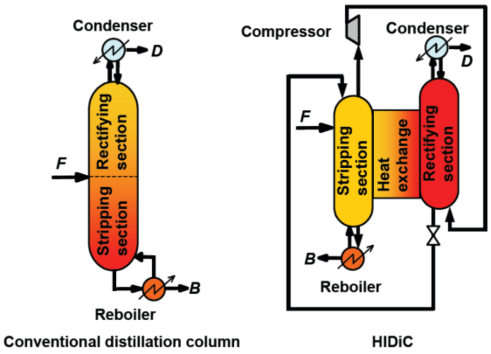

Figure 1: Basic structure of the conventional distillation column and the HIDiC

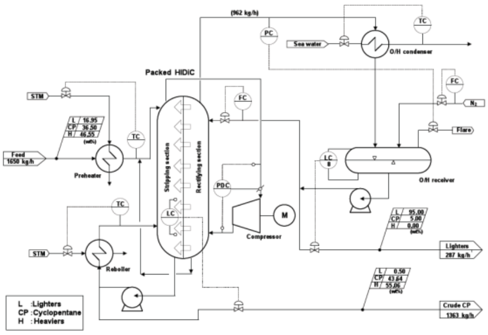

Figure 2: Process flow diagram of the HIDiC pilot plant

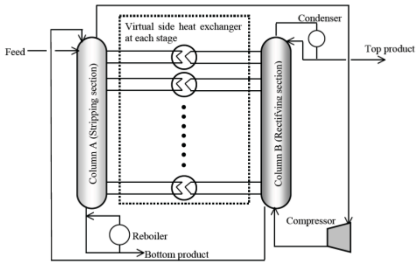

Figure 3: Imaginary flow configurations of the HIDiC for the simulation on Pro/II®

The as-developed models have been used as pilot plant for HIDiC, and their performances and energy-saving ratio have also investigated.

2. Simulations

In this study, the HIDiC is simulated by using a process simulator. As shown in Figure 3, the basic flow configuration of HIDiC was altered to a twin column type model having separately a rectifying column and a stripping column only for computer simulation. An imaginary heat exchanger was installed on each couple of stages matched between the rectifying and stripping columns. This imaginary flow configuration was simulated. Inside-out algorithm was employed for distillation calculation since the mixture to be separated consists of hydrocarbons and the algorithm is suitable for mixtures whose phase equilibria are close to ideal ones. The material balance based on the feed and the bottom and overhead products is assumed to be the same as the operating data of the commercial column (Horiuchi et al., 2005). The total material balance of this process is assumed to be the same as in the commercial scale conventional pentane column (55 stages of bubble cap tray) for comparison of the computer simulation with the actual operating data. The composition and flow rate of the feed and the overhead and bottom products given as the specifications in Table 1 are the same as those of the commercial pentane column. Specifications of products equivalent to the existent conventional distillation column are set as follows: cyclopentane in overhead product is 5.0% and n-pentane and 2,2-dimethylbutane in bottom product are 0.5% in total.

3. Results and discussion

3.1 Vapour and liquid flow rate and temperature profiles

Figure 4 shows the vapour and liquid flow rates profiles of the HIDiC with 72 stages at the compression ratio of 1.8, which is defined by the pressure ratio of the bottom of the rectifying section to the top of the stripping section. In the separation of ideal mixtures by conventional distillation columns with a single feed and no side draws, vapour flow rates are almost constant over the whole column height, and the liquid flow rates in the rectifying and the stripping sections are also almost constant, respectively (Horiuchi et al, 2005). In the HIDiC system, however, both the flow rates vary along the column height because each stage in the rectifying section has a virtual condenser to produce additional liquid while each stage in the stripping section has a virtual reboiler to produce additional vapor. This suggests that the column diameter should be altered with the column height in the structural design of HIDiC system in order to keep the vapor velocity, i.e. F-factor, as constant as possible. The column diameter should be increased upward in the stripping section and downward in the rectifying section corresponding to the vapour and liquid flow rates in Figure 4. Figure 5 also shows the temperature profile of the HIDiC with 35 theoretical stages at the compression ration of 1.8. As distinct from a conventional distillation column, the HIDiC system keeps the temperature higher in the rectifying section than in the stripping section by compressing the vapour leaving the top of stripping section into the bottom of rectifying section. The temperature difference between the rectifying and the stripping section on each stage causes the internal energy integration leading to energy saving. Figure 5 shows that the temperature difference becomes larger in the lower section than in the upper section. This suggests that vapour is effectively produced in the lower part of the stripping section.

Table 1: Pressure drop and column pressures in the simulation

	Conventional	HIDiC
ΔP [kPa/column]	19.61	-
ΔP [kPa/stage]	-	0.1373
P_{rec} [kPa]	101.3	182.4, 202.6
P_{str} [kPa]	101.3	101.3

3.2 Estimation of energy savings by HIDiC

The minimum reflux ratio for the conventional distillation column was calculated by changing the total stage number under the same conditions of the feed, the overhead and the products as for the HIDiC system of interest.

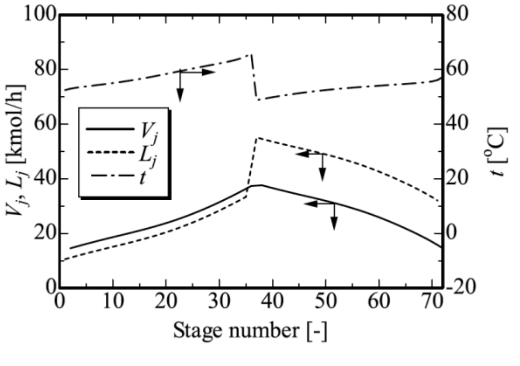

Figure 4: Profiles of vapour and liquid flow rates and temperatures in the HIDiC at the compression ratio of 1.8

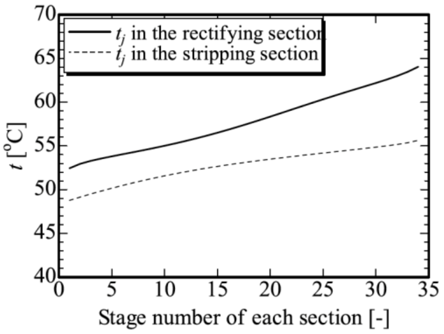

Figure 5: Temperature difference between the rectifying and the stripping section of the HIDiC at the compression ratio of 1.8

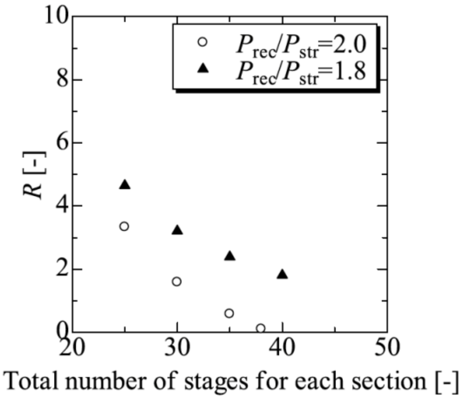

Figure 6: Reflux ratios required to satisfy the product specifications by the HIDiC

The value for U is adopted from the experimental data and UA is fixed at 800 kcal/h/K/stage or 926 W/K/stage throughout this study. Figure 6 shows the reflux ratios of the HIDiC obtained by varying the number of stage of both the sections in two conditions of compression ratio 1.8 and 2.0. It shows that the HIDiC reflux ratio is much less than the minimum reflux ratio of the conventional column. In general, the reflux ratio can be reduced by increasing the number of stages. Especially in the case when the number of stages is more than 38 at the compression ratio of 2.0, the zero reflux operation can be carried out.

4. Conclusions

In this study, computer-aided analysis of energy saving by the HIDiC was conducted on a process simulator. The application of the HIDiC technology to the commercial scale existent conventional distillation column was simulated and energy consumptions of the HIDiC were compared with that of the conventional distillation column operated at the minimum reflux ratio. When the value of UA for the HIDiC was fixed at 926 W/K/stage throughout the column, energy saving rate of 50 % was expected if the HIDiC has 38 stages and is operated at the compression ratio of 2.0. The simulation results also suggested that the HIDiC can be operated at the zero external reflux condition.

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