고효율 증류탑의 열역학적 특성과 응용

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Thermodynamic Characteristic and Application of Energy-Efficient Distillation Columns

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1. Introduction

Though sufficient contact time for mass transfer between the vapor and liquid in the trays is necessary, the mass transfer occurs momentarily due to the limited residence time in a conventional distillation column. In order to expand the short liquid residence time, a certain amount of reflux flow is used in adiabatic distillation operation. Because of the reflux flow the same amount of liquid added to the overhead product has to be vaporized in a reboiler consuming a large amount of energy. In the conventional distillation none of the energy is recovered unless the overhead condenser is heat-integrated. Even from the heat recovery, the quality of the recovered energy is much less than the supplied heat at the reboiler due to the difference of boiling temperatures of overhead and bottom products. In the ideal diabatic operation of a vertical distillation column, the residence time can be increased without the reflux flow

Distillation is a fully developed separation technology with a long history of wide utilization in chemical process industries, but its consumption of a large amount of energy calls for a variety of energy-efficient distillation systems. There are three structural improvements for the reduction of energy demand in the distillation column. The divided-wall column (DWC), also known as the Petlyuk column, has been successfully implemented in field applications[1-4]. It has more efficient column profile than that in a conventional distillation system, but its application is limited to the separation of ternary mixtures in terms of major components. Two consecutive distillation columns in the conventional distillation system are replaced with the single DWC, which discourages the field engineers from its utilization in practice due to its limited applicability. Secondly diabatic distillation reduces the temperature difference between the temperatures of heating and cooling media by employing small heat exchangers in all trays for the replacement of reboiler and condenser. The smaller temperature difference increases the thermodynamic efficiency of the diabatic distillation column. Thirdly the internally heat-integrated distillation column (HIDiC) not only uses the structure of diabatic distillation but also recovers the heat released from the condenser and supplies it to the reboiler by raising the operating pressure in the rectifying section of the column. The reboiler temperature is higher than that of the condenser in a conventional distillation column. Therefore, a vapor compression or vacuum was applied to reverse the temperature difference in the HIDiC. The internal heat integration has been applied to the multi-component separation. The manipulation of the operating pressure was also applied to the direct heat integration between the condenser and reboiler due to their unfavorable temperature difference.

The internally heat-integrated distillation column (HIDiC) utilizes the heat removed from the upper section of a binary column, rectifying section, to heat its lower section, stripping section. This heat integration is accomplished by using the two sections in a single column sharing the same column wall for heat transfer. One problem with the scheme is that the temperature in the upper section is lower than the temperature in the lower section, while heat transfers from the upper to the lower. Therefore, vapor compression is necessary for the elevation of the upper section temperature, and the utilization of a compressor involves operational difficulty due to its electrical operation and maintenance. An ideal HIDiC does not require external heat supply except the electricity used by the compressor, but the heat exchangers are necessary for the startup and control of the column. There has been some attempt to eliminate the compressor in the HIDiC. In the development of compressor-free HIDiC, the authors, who have a long experience in the development of commercially applicable HIDiC in industry, listed the difficulties associated with the compressor as follows:

- A big turbo-blower compressing a large volume of vapor is expensive.
- The original HIDiC is legally classified as a pressure vessel subject to the safety regulation.
- The HIDiC cannot be applied for such feeds containing dirty, sticky, corrosive and heat-sensitive compounds.
- Start-up and shut-down as well as normal operation are not easy.

These problems have been indicated by field engineers in Japan, and therefore the authors proposed the compressor-free system to promote the application of HIDiC in industry. The distillation system has two separate columns of different operating pressures. The high pressure column utilizes high pressure steam, and the vapor from the column supplies a low pressure vapor to the low pressure column through an expansion valve. The pressure difference provides the driving force of temperature gap for the heat transfer from the rectifying column of high pressure to the stripping column of low pressure. Recently, the heat-integration with external heat exchangers has been proposed: between condenser and reboiler[7] and between trays in rectifying and stripping sections.

When a diabatic distillation column is utilized in horizontal distillation, the residence time of liquid flow can be adjusted without the external reflux flow. Therefore no condensation of vapor product is necessary, unless liquid feed is necessary in the following process using the product as its feed. The liquid flow in the horizontal column is an internal reflux flow, and the reflux flow in the conventional distillation column is an external reflux flow. The vapor of high temperature, high enthalpy, becomes the vapor of low enthalpy, when it leaves the column in the conventional distillation. Because of the external reflux flow the amount of vapor is much more than the amount of overhead product. Moreover the vapor from the top has to be condensed for the external liquid reflux. The loss of energy depends upon three factors: the temperature drop in vapor between top and bottom of the column, large amount of vapor and vapor condensation. When a horizontal diabatic distillation is utilized, no excess vaporization is necessary The exact amount of vapor product leaves the column. If the vapor can be used as feed in the following process, no condensation is required. The only necessary heat is consumed in the diabatic horizontal distillation, and no external reflux flow is necessary. The elimination of the external reflux flow reduces the energy consumption in the distillation.

In this study a horizontal diabatic distillation is proposed to take advantage of adjustable residence time of liquid in the column, which does not require the external reflux flow and subsequently reduces energy demand. The separation performance and energy reduction are investigated through the experiment and simulation. The horizontal packed column is composed of the rectifying and stripping sections, while the feed is provided in the middle. Through the glass column wall heat is supplied to the stripping section and is removed from the rectifying section. The product compositions are computed from a rate-based model, and the results are compared with the experimental outcome. A system of methanol-*n*-propanol mixture is used here. The energy demand of the proposed distillation is compared with that of the conventional distillation using simulation results.

2. Column Structure and Deisgn

The design of this study targets to raise the thermodynamic efficiency of distillation process. In a conventional distillation column, a large amount of vapor having high enthalpy at high temperature goes through the column and exits at low temperature. The enthalpy loss between the entering and leaving vapors is irreversible. Reducing the amount of vapor minimizes the loss, but the reduction is limited due to the reflux flow. Most of the heating duty at the reboiler comes from the recycled liquid flow of the reflux. In the vertical distillation column with adiabatic operation, the residence time of liquid holdup inside the column section is short because of the gravitational flow of the liquid. Therefore the reflux flow is inevitable to provide the sufficient contact for the vapor-liquid mass transfer. The fact that raising the reflux flow improves the product specification indicates the short residence time of the vertical column. On the other hand, the reflux flow can be eliminated in the horizontal diabatic distillation as shown in Figure 3. Without the reflux flow the residence time of liquid is manipulated with the column inclination and heat supply The proposed structure of distillation system in this study has been modified from a conventional two column system of ternary separation. An internally heat-integrated column is attached between the two columns of the conventional distillation system. Because the design and control of the conventional system are simple and easy, the system has been adopted as a standard configuration in field applications until the recent issue of heat duty reduction arises in the distillation column operation. The two columns are operated as a binary column in the exactly same manner. However, the thermodynamic efficiency of the system is significantly low due to the remixing of the intermediate component in the second column.

An internally heat-integrated distillation has been introduced for binary separation as an energy-efficient distillation column. When the heat integration of an internally heat-integrated distillation column demonstrated in Figure 1 is applied to the conventional distillation system, a new partially heat-integrated distillation system can be yielded as given in Figure 2. The concept of the system is that the heat removed from the upper section of the second column is supplied to the lower section of the first in tray-by-tray manner. The direct heat utilization from the condenser of the second column to the reboiler of the first is not possible due to the negative temperature difference. It can be available with a large elevation of the column pressure of the second column. In practical implementation the two existing columns of the conventional system can be employed the columns, and a new internally heat-integrated column is installed between the two columns.

3. Results and Discussion

The horizontal distillation using a 40 mm glass column with external heating was conducted with a feed of methanol/*n*-propanol mixture, and the following experimental results were obtained and analyzed by comparing with the simulation results. The experimental results of the horizontal distillation were compared with the simulated performance of the conventional vertical distillation column using the HYSYS. When the average value of the height equivalent to the theoretical plate (HETP)was applied to the distillation column of this study, the tray number was five. In the HYSYS simulation of the vertical column, three trays with a reboiler and a partial condenser were employed in the simulated system. Note that neither reboiler nor condenser was used in the diabatic distillation. When a partial condenser and a reboiler are included in the stage number, a 3-stage conventional distillation column is equivalent to a 5-stage diabatic horizontal column. The comparison indicates the horizontal distillation requires 25.7 % less heating energy. A comparison of diababic and conventional vertical columns was conducted in Nakaiwa et al., and the study shows 41 % energy saving from the conventional column simulated with the reflux ratio of 1.5. The reflux ratio of 1.2 and energy saving of this study are comparable to the vertical diabatic distillation.

When the same separation was obtained with a conventional vertical column, the heat duty was calculated using the HYSYS. The heat duty of the horizontal distillation of this study was 25.7 % less than that of the conventional distillation. The minimum reflux ratio is 0.7 at an energy consumption of 335 W for the same product specification. When the reflux ratio of 1.2 times the minimum is applied, 11 trays and a partial condenser and a reboiler are necessary to yield the same products and the energy consumption is 362 W. Using the five stages including the partial condenser and reboiler used in this study, the reflux ratio of 1.2 and the energy consumption of 443 W calculated from the simulation of the vertical column are reasonable. A large amount of vapor used in the conventional distillation is eliminated in the horizontal distillation to reduce the heat demand. The horizontal distillation column saves energy, because a lower reflux rate is required. The problem of the high energy demand in the conventional distillation is originated from its vertical structure and external reflux flow due to adiabatic operation. Though several structures of energy-efficient distillation have been proposed and one of them has been commercialized to prove its performance, no distillation column utilizing the horizontal column with diabatic operation has been introduced yet.

References

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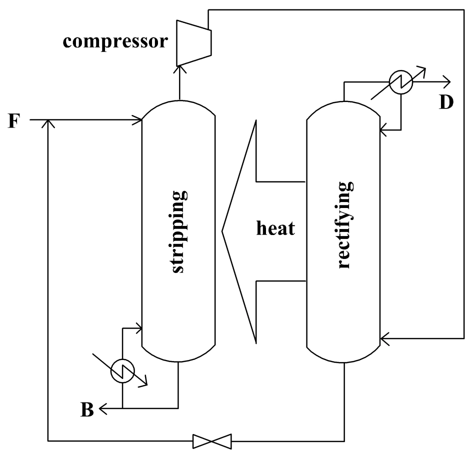

Fig. 1. A schematic diagram of an internally heat-integrated distillation column for binary separation.

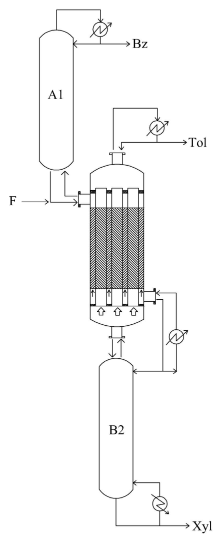

Fig. 2. A schematic diagram of the proposed heat-integrated distillation column.

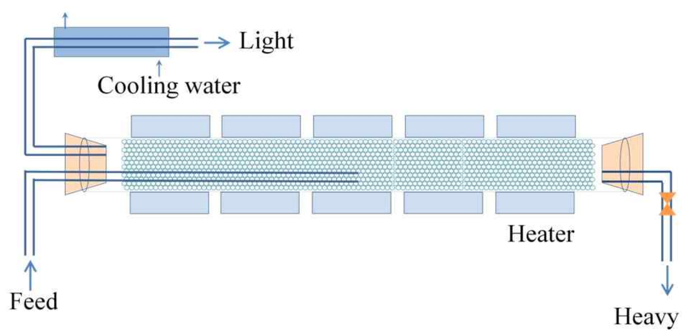

Fig. 3. Schematic diagram of the experimental setup of horizontal diabatic distillation showing five sections of heating and temperature control.