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INVITED REVIEW PAPER

Design and control of energy-efficient distillation columns

Young Han Kim[†]

Department of Chemical Engineering, Dong-A University, Busan 49315, Korea
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Abstract−Distillation is the best option for the separation of hydrocarbon mixtures, unless the boiling points of the constituents are close together. Despite being widely utilized in field applications, the high energy demand of distillation calls for efficient columns in order to save energy. The efficient divided wall column (DWC), diabatic distillation column, and internally heat-integrated distillation column (HIDiC) are introduced here, and the design and control of the columns are briefly reviewed. The practical applications of the columns in the processes of natural gas production from raw gas drawn from underground and benzene separation from naphtha reformate are presented to show the energy-saving performance of the energy-efficient distillation columns. The side-rectifier DWC reduced the heating duty of the conventional system by 5.9%, and provided a compact construction, replacing the three-column conventional system with a single column suitable for offshore application. Moreover, the controllability of DWC was improved by utilizing the side-rectifier. The benzene removal process utilizing the extended DWC lowered the heating duty of the whole conventional process by 56.8%.

Keywords: Energy-efficient Distillation, Divided Wall Column, Diabatic Distillation, Internally Heat-integrated Distillation, Distillation Column Design

INTRODUCTION

Unless the boiling points of components in a mixture are close together, distillation is the first choice among various separation techniques due to its well-established methodology. Distillation is a fully developed separation technology with a long history of wide utilization in chemical process industries, however, its consumption of a large amount of energy calls for a variety of energy-efficient distillation systems [1,2]. There have been three major developments in technology to reduce the energy demand in distillation columns [3,4]. The divided wall column (DWC), also known as the Petlyuk column, has been successfully implemented in field applications [5-9]. It has a more efficient column profile than that in a conventional distillation system; however, 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 a single DWC, which simplifies the construction. The combination of two columns eliminates some of the manipulated variables used in the operation of the two-column process, which makes column operation difficult. In that regard, field engineers have been reluctant to use the DWC. However, its application has been extended to extractive [10-14], azeotropic [15], and reactive [16-19] distillation. Moreover, diabatic distillation reduces the temperature difference between heating and cooling media by employing small heat exchangers in each tray to replace the reboiler and condenser. The smaller temperature difference in the heat exchangers increases the thermodynamic efficiency of the diabatic distillation column [20-22]. The internally heat-integrated distillation column (HIDiC) not only has the same structure of a diabatic distillation column, 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 [23,24]. The reboiler temperature is higher than that of the condenser in a conventional distillation column. Therefore, the operating pressure in the rectifying section is elevated, or that in the stripping section lowered, to reverse the temperature difference in the HIDiC. Internal heat integration has also been applied to multicomponent separation [25,26]. The operating pressure was manipulated in the direct heat integration between the condenser and reboiler due to their unfavorable temperature difference of heat transfer [27,28].

In the present study, we review the recently published design and control of energy-efficient distillation columns. The following sections outline the design and control of energy-efficient distillation columns and examples of their application.

DIVIDED WALL COLUMNS

Divided wall columns (DWC) are the most widely practiced distillation technique among the various energy-efficient distillation systems available, and many studies have presented their energy saving performance [29]. In principle, the structure of DWCs, as shown in Fig. 1(a), is the same as Petlyuk columns, illustrated in Fig. 1(b), which is used in the design of DWCs using commercial design software.

1. Design of Divided Wall Columns [30]

There are several design procedures for DWCs: 3-column modelling, minimum structure design, and optimal design with numerical programming. In the 3-column modelling [31-33], the prefractionator is assumed to be a binary distillation column with a par-

[†]To whom correspondence should be addressed.
E-mail: yhkim@mail.donga.ac.kr

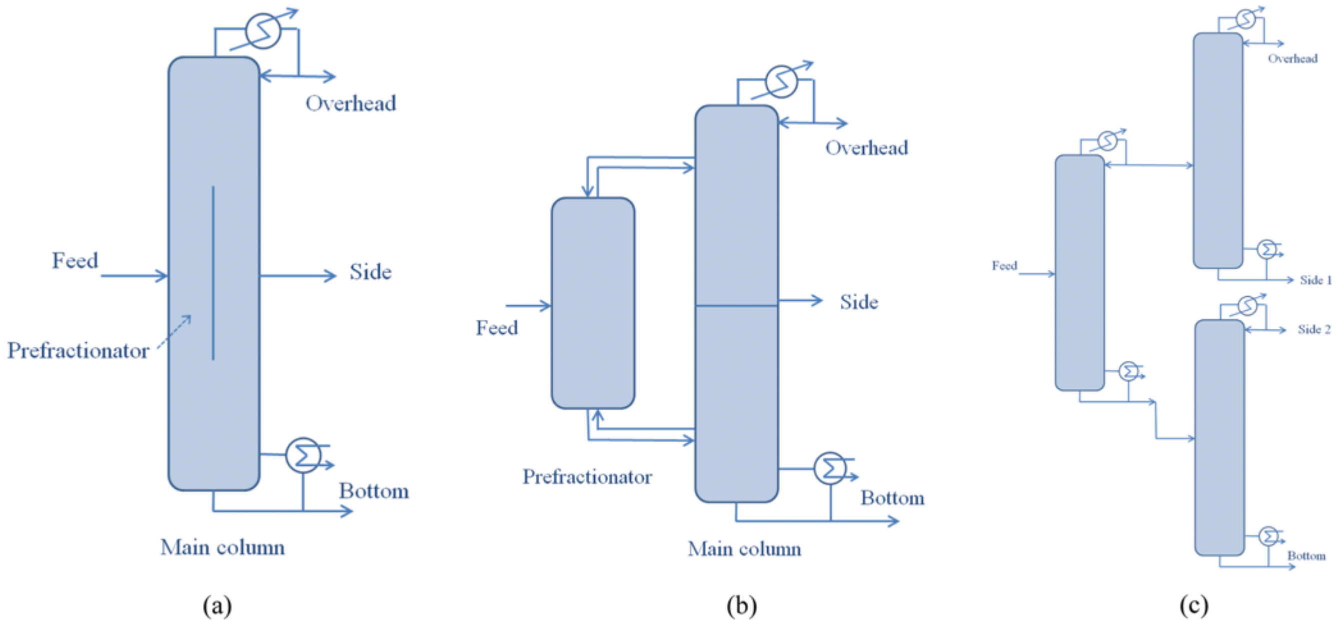


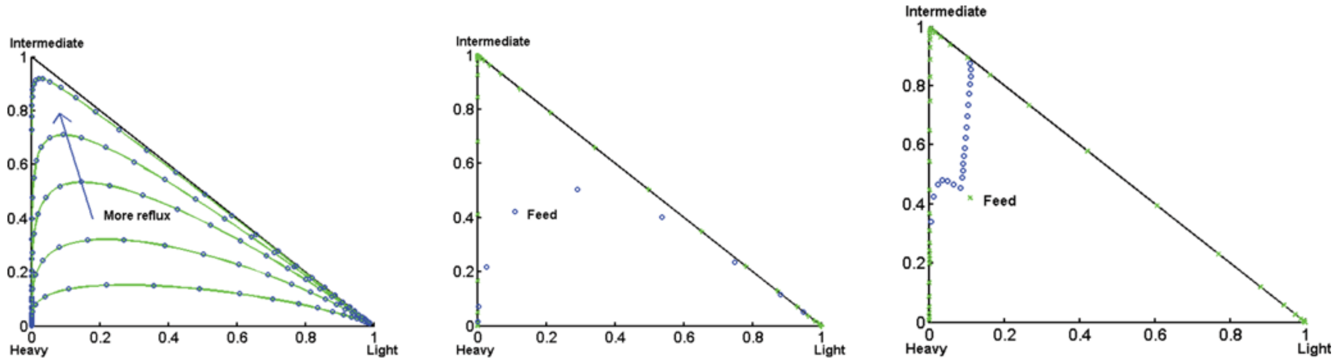
Fig. 1. Schematic diagram of (a) a divided wall column (DWC), (b) the Petlyuk column, and (c) a 3-column model [31].

tial condenser and a partial reboiler, providing interlinking vapor and liquid flow to the two main columns, as demonstrated in Fig. 1(c). The three-column design utilizes the Fenske-Underwood-Gilliland shortcut procedure. The separate design results of the three columns are combined as a Petlyuk column, and subsequently adjusted for modification.

Commercial software is widely used in the design of distillation columns, in which the column structure and operating pressure are required to initiate the column simulation in order to find a product specification for a given feed [30]. The simulation continues until the computed product satisfies the design specification with the minimum reflux flow. Therefore, the column structure information plays an important role in the commercial software design of the column; otherwise, the minimum reflux must be iteratively searched for. In the design of a conventional distillation column, the number of trays is calculated by setting the reflux flow rate at between 1.2 and 2.0 times the minimum reflux flow rate [34]. Without the reflux rate, an optimization of the minimized total annual expense, including capital cost and energy expense, is conducted to find the optimum tray number and reflux. When this procedure, providing the column structure in the beginning, is applied to the design of the DWC, the total number of trays, the feed tray, the side draw tray, and the location of interlinking streams between the prefractionator and the main column are necessary as structural information. Although the short-cut design equations for multi-component distillation can be implemented to the partitioned columns [31], the design is not satisfactory for rigorous simulation. Moreover, many combinations of tray numbers and interlinking locations do not result in a convergent solution, since the matched composition between the prefractionator and the main column of the interlinked trays is not available. The unavailability is located in a hole of the operating conditions of the DWC [35-37].

When the structure of the DWC is given, the simulation using the commercial software is ready to examine the operating conditions for a desired specification of product. A procedure to elucidate the structure using the minimum structure has been proposed [38-40]. When the column profile of the DWC follows one of the residue curves, the thermodynamic efficiency of the column is ideal, since the residue curves denote the composition profile of a packed distillation column in total reflux operation [41]. Despite the fact that the residue curves represent the liquid composition profile of a packed column, it is generally assumed that they are accurate representations of the profile of a tray column at total reflux [41-43]. It is noteworthy that the shape of the composition profile of a tray column is similar to the curves; thus, comparing the column profile of the DWC with the residue curves reveals the efficiency of a certain column structure. The increased liquid flow shifts the curve close to the intermediate components, but the lightest and heaviest products change little in their composition, as illustrated by the residue curves in Fig. 2(a). In other words, the composition of the side products determines the residue curve for the column profile of the main column, and the path of distillation of the main column that produces side draw is also determined by the composition of the side product. If the feed composition is not far from the feed tray composition, it also decides the path of prefractionation.

The minimum structure represents the ideal highest thermodynamic efficiency of the distillation column. For a practical column, twice the number of trays than the minimum structure are used when applying the design practice of a conventional distillation column, in which proportionally increasing the number of column structures, total number of trays, feed and side draw trays, and interlinking trays, sustains high efficiency. Even when the number of trays is increased by a factor of two, the structure remains optimal. This practice has been implemented in the design of binary distillation columns such as the McCabe-Thiele design [34]. A ratio of two was adopted from the literature [44,45], which is within the



(a) (b) (c)

Fig. 2. Residue curves in (a) a ternary system, (b) column profiles of the Petlyuk column in minimum structure, and (c) those in the practical design [88].

range used in industrial practice. The relationship between the reflux ratio and the tray number indicates that, while the reflux ratio varies between 1.1 and 1.5 times the minimum, the tray number is between 1.7 and 2.6 times the minimum. For the commonly used reflux ratio of 1.3 times the minimum reflux, twice the minimum number of trays is a reasonable design for a usual distillation column [45].

The minimum number of trays in a distillation column is computed in a total reflux operation in which the vapor composition of a stage is the same as the liquid composition of one stage above that stage. Assuming that the feed stage has an equal liquid composition to the composition of a saturated liquid feed, and the tray efficiency is ideal, one can calculate the liquid composition of the stages above the feed tray from Eq. (1).

$$x_{n+1,i}=\alpha_i x_{n,i}/\sum_j \alpha_j x_{n,j} \tag{1}$$

where the subscript n denotes the n^{th} tray counted from the bottom and α is the relative volatility. For a non-ideal system, an equilibrium constant computed from the equilibrium relationship can replace the relative volatility with an iteratively updated constant [39]. Similarly, the liquid composition of the stages below the feed tray is given as:

$$x_{n-1,i}=x_{n,i}/\left[\alpha_i\sum_j (x_{n,j}/\alpha_j)\right] \tag{2}$$

This stage-to-stage design procedure is applied to the main column, beginning with the composition of the side product. The interlinking locations between the main column and the prefractionator are determined by comparing the profiles of the liquid composition of the main column and prefractionator. The locations of the feed and side product trays are subsequently counted from the stage-to-stage computation. For a better understanding of the procedure, the results of the stage-to-stage computation are given in Fig. 2(b), where circles are the prefractionator and times symbols are the main column. This is the outcome of the BTX process [40].

The first part of the structural design, the minimum numbers of trays, of the present study is based on the assumption of total reflux operation and ideal tray efficiency, which indicate an equilibrium process of no irreversible mixing. In other words, the maximum thermodynamic efficiency is yielded from the designed structure of a distillation system. The practical structure used in the real column design of the DWC was twice the number than in the minimum structure as explained above, and the column profile as shown in Fig. 2(c) was found from the simulation of the commercial design software. The operating conditions of the designed DWC were found from the iterative computation of the desired specification of products.

Many distillation column design studies have been introduced using numerical programming, which handle a variety of distillation systems of different structures for conventional and energy-efficient distillation using multi-component separation [46,47]. The sections of rectifying and stripping are widely combined for the optimized objective of total annual cost (TAC). Searching the TACs of many possible combinations of sections using a numerical programming technique gives the optimum solution. However, the generalized procedure often misses the true solution of the energy-efficient distillation system for a certain purpose of separation.

2. Control of Divided Wall Columns

The DWC has poor operability due to the small number of externally manipulated variables for the control of product specification. All the inter-linking streams between the prefractionator and the main column of the DWC are internal and unavailable for manipulation. Therefore, a sufficient margin of product specification in the column design has been suggested by Wolff and Skogestad [35] to compensate for the difficulty in control. When the DWC is constructed in the Petlyuk column as shown in Fig. 1(b), which has the same thermodynamic efficiency as the DWC, the internal streams become external, and more variables are available for manipulation. Several modifications have been introduced for easy operation [48-52]. The manipulation of vapor flow between the prefractionator and the main column is more difficult than the liquid flow, due to its large volume. The column operating pressure in the sections of the prefractionator and the main column was adjusted for easy vapor flow, such that the vapor flows from the stripping section to the prefractionator and to the rectifying section of the main column with sequentially reduced pressure [49]. On the other hand, the liquid flow in reverse pressure, is easily available through the use of a mechanical pump. An improvement in operability with the additional manipulated variables has been demonstrated with the side-column DWC [53,54].

DIABATIC DISTILLATION COLUMNS

There are three types of distillation columns that have high energy efficiency. One of these, a diabatic distillation column, has small heat exchangers inside the column trays [22,55,56]. The arrangement provides a lower temperature difference in heat transfer compared with the temperatures of the reboiler and condenser in adiabatic distillation. Thus, the thermodynamic efficiency of diabatic distillation is higher than that of adiabatic, since the energy loss in adiabatic distillation is much larger.

1. Vertical Diabatic Distillation Columns

A conventional distillation column consists of a column, a condenser, and a reboiler. The condenser, attached at the top of the column, cools the vapor from the column to liquid, of which a portion returns to the top of the column providing vapor and liquid contact of mass transfer. On the other hand, the reboiler heats the liquid from the bottom of the column to provide the returning vapor to the column. The two heat exchangers work at the two extreme temperatures of the column, resulting in a large energy loss of the heat transfer media, cooling water and steam. A diabatic distillation column has small heat exchangers in each and every tray, replacing the reboiler and condenser of a conventional distillation column, as illustrated in Fig. 3. The duties of the reboiler and condenser are significantly reduced, although the total duty including the duties of in-tray heat exchangers is 16% lower [22]. Since the heat transfers at a lower temperature difference in the in-tray heat exchangers, the energy loss in diabatic distillation is much less than in the conventional system. In the conventional system, two heat exchangers, a reboiler, and a condenser handle all the column heat transfer, and the heat transfer occurs at a large temperature

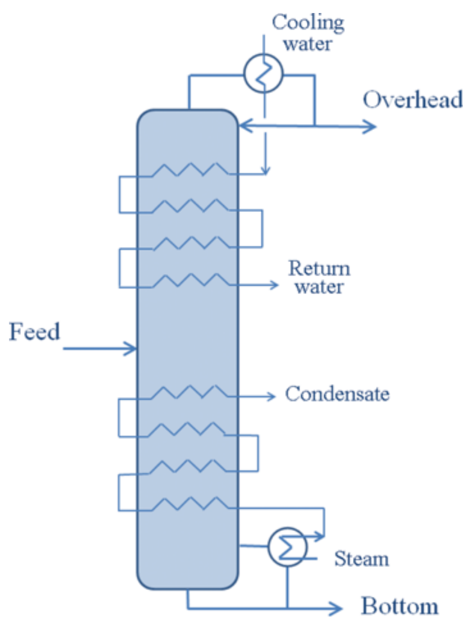


Fig. 3. Schematic diagram of a diabatic distillation column [22].

difference, leading to a large energy loss. In practice, the installation of small heat exchangers in every tray is difficult, and the maintenance is also complicated. The fact that the temperature of the returning water from the diabatic distillation column, as seen in Fig. 3, is much higher than the returning water temperature from the conventional distillation column, indicates the high thermodynamic efficiency of diabatic distillation. Similarly, the condensate temperature in diabatic distillation is much lower than in conventional distillation, and shows more efficient utilization of steam at the reboiler. Internally heat-integrated distillation is a modification of diabatic distillation, replacing the cumbersome in-tray heat exchangers with a compressor.

2. Horizontal Diabatic Distillation Columns [3]

When a diabatic distillation column is utilized in horizontal distillation, the residence time of liquid flow can be adjusted without an 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, while the reflux flow in the conventional distillation column is an external reflux flow. Vapor of high temperature and high enthalpy becomes the vapor of low enthalpy when it leaves the column in conventional distillation. Due to the external reflux flow, the amount of vapor is much greater than the amount of overhead product. Moreover, the vapor from the top must be condensed for external liquid reflux. These are responsible for the large energy demand in conventional vertical distillation. Fig. 4 illustrates horizontal distillation. The heat supply at the stripping section generates vapor, and the cooling at the rectifying section provides liquid flow. The inclined column makes the liquid flow to the heavy product side, while vapor flows to the light product side, coming into contact with the liquid in its path.

The loss of energy depends on three factors: the temperature drop of the vapor between the top and bottom of the column, the large amount of vapor, and vapor condensation. When horizontal diabatic distillation is used, no excess vaporization is necessary, and an exact amount of vapor product leaves the column. If the vapor can be used as feed in the following process, no condensation is required. No excessive energy is consumed in horizontal diabatic distillation, and no external reflux flow is necessary. The elimination of external reflux flow reduces the energy consumption in distillation [3,57,58]. The problem of horizontal distillation in adiabatic operation is how to provide sufficient interfacial area for mass transfer between the vapor and the liquid. The spreading of the liquid to increase the interfacial area is not possible with the horizontal liquid flow. In a vertical column, expansion of the area has been created from the improved mechanical design of trays and developed packing materials. However, these developments in

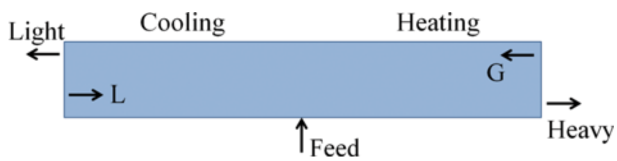


Fig. 4. Liquid and gas flows with diabatic heat transfer in a horizontal distillation column [3].

the vertical column are not applicable to the horizontal column due to the limited dispersion of liquid. The horizontal distillation of methanol/*n*-propanol has been conducted in a 40-mm circular glass column packed with a 6-mm Raschig ring [3,57]. The computed energy requirement of the horizontal diabatic distillation column was 25.7% less than that of the conventional distillation column, calculated from the HYSYS simulation for a product purity of 0.89 mol fraction in a vertical column with five stages.

The packing for vertical columns may not be suitable for horizontal columns due to the difference in vapor and liquid flow directions. A novel design of packing is necessary for the horizontal columns. In previous studies of horizontal distillation, fiber glass [59], wire brush [60], wire gauze [61], nonwoven fabric [61], and metal foam [62] have been used for packing, which are good wet, with the capillary transport of liquid. The metal foam can be a packing material for horizontal distillation due to its capillary liquid transport and high durability against heat and corrosion [3].

INTERNALLY HEAT-INTEGRATED DISTILLATION COLUMNS (HIDiCs)

The internally heat-integrated distillation column (HIDiC) utilizes the heat removed from the upper section of a binary column, the rectifying section, to heat its lower section, the stripping section. This heat integration is accomplished by the use of the two sections in a single column sharing the same column wall for heat transfer. One problem with this 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 section [63]. 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 an external heat supply, except the electricity used by the compressor; however, heat exchangers are necessary for the startup and control of the column. There has been some attempt to eliminate the compressor in the HIDiC.

1. Design of Internally Heat-integrated Distillation Columns [64]

The HIDiC is designed by the use of two separate columns, as shown in Fig. 5, which satisfy the requirement of heat transfer, amount of heat transfer and temperature difference in pairing stages [65]. A reasonable temperature difference needs to be specified together with either the duty of the exchanger or the stream flow rates. This technique provides the calculations of the heat transfer area simultaneously with the column model calculations, using the stage equilibrium between the vapor, liquid, and material balance. The heat integration is performed by adding heat loads to stripping stages, and removing the same amounts of heat from the rectifying stages. Subsequently, the calculations of the heat transfer area are performed separately when the column simulation has converged. Such a design technique is a two-step procedure. The design task includes calculations of the compressor, condenser and reboiler duties, stage heat rates, and the heat transfer area required.

2. Partially and Internally Heat-integrated Distillation Columns

When the heat integration of an internally heat-integrated distillation column is applied to two conventional distillation systems, a partially heat-integrated distillation system can be yielded, as given in Fig. 6. Although the heat integration on this system is partial, it does not require vapor compression as in the full heat-integration. The use of a compressor causes many problems, which makes field engineers reluctant to utilize the HIDiC. 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 a 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 upon a large elevation in column pressure of the second column. In practical implementation, the two existing columns of the conventional sys-

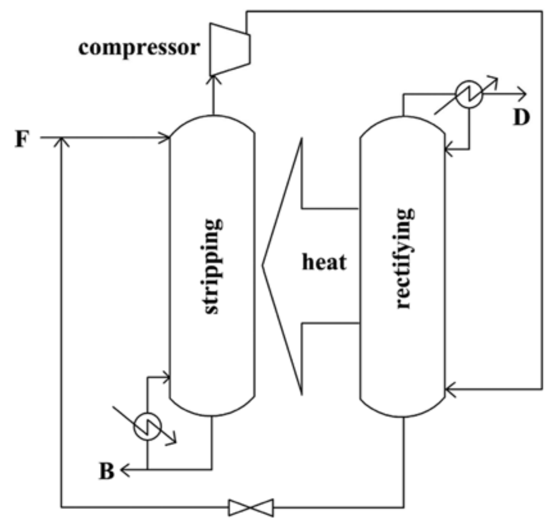


Fig. 5. Schematic diagram of an internally heat-integrated distillation column (HIDiC) [24].

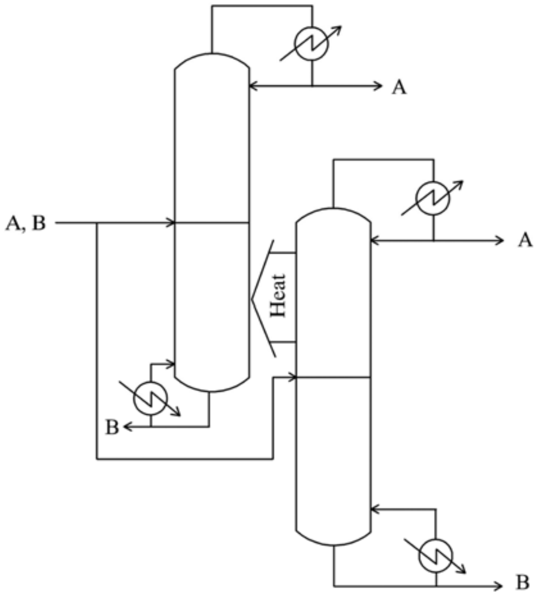


Fig. 6. Schematic diagram of a partially and internally heat-integrated distillation column [72].

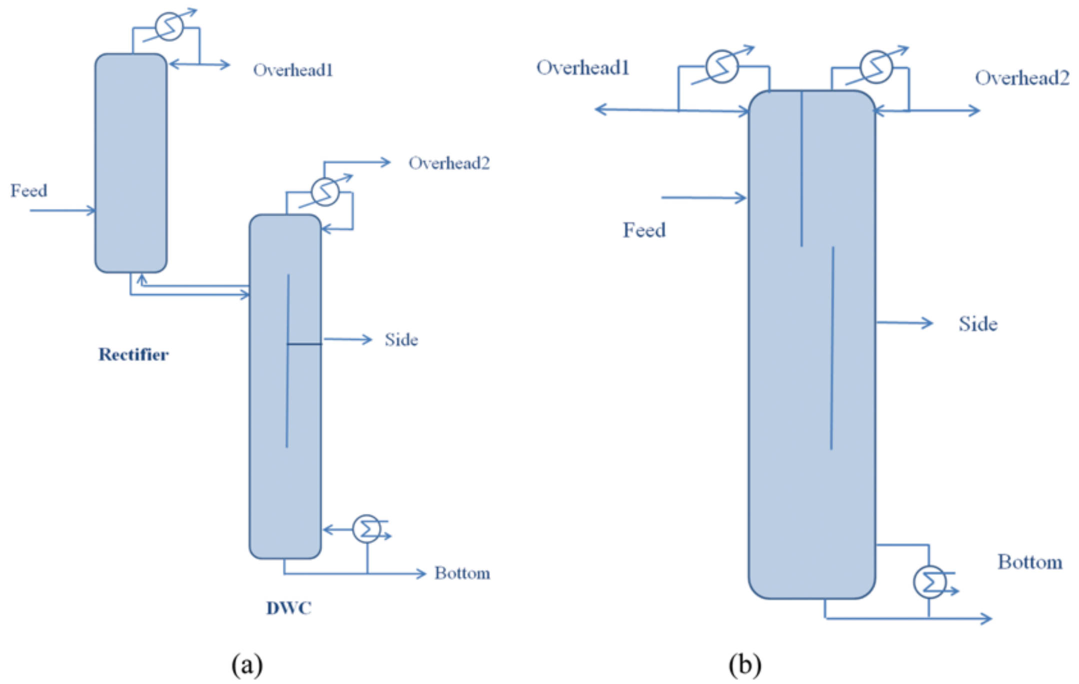


Fig. 7. Schematic diagram of (a) a side-rectifier DWC and (b) its single-column construction [54].

tem can be employed as heat-integrated columns, in which a novel internally heat-integrated column is installed between the two columns [25,26,66,67]. The novel distillation system is modified from the conventional distillation system of two binary distillation columns, and therefore, the structural design of the system can be directly adopted from the conventional system. The structural design of the conventional system is easily obtained using the commercial design software, when the column pressure and compositions of the feed and products are given. The liquid flow rates are iteratively computed for minimum heat requirement. The column structure of the newly introduced section of heat integration is determined from the design of the conventional system.

PRACTICAL APPLICATIONS

Many distillation columns with high energy efficiency have been successfully operated in field applications [5-8]. In this section, the recent studies of DWC utilization in whole processes of separation are introduced.

1. LNG Separation [53]

Raw natural gas from gas wells contains liquid components of oil and water, which are separated through the multiple separators having successively reduced pressures up to 20 kPa to maximize gas recovery and to stabilize the crude oil [68]. The processed gas is compressed to a high pressure to minimize the amount of processing equipment in the next stage. The feed components have a wide variation of volatility, but methane is more than 86%. The first column in the conventional gas separation system processes most of the feed due to the large amount of methane, and a specially-designed distillation system processing the feed is employed in the gas separation. Although an onshore separation system uses five columns, as demonstrated in Lee et al. [69,70], the number of columns is limited in the offshore operation. A three-column offshore process is conventionally utilized. When the prefractionator of the Petlyuk column accommodates a small column on its top, the pretreatment column for the common DWC used in the previous studies [69,71,72] can be eliminated in order to make the whole distillation system a single column. In practice, the proposed column becomes a side-rectifier DWC, as illustrated in Fig. 7(a), and it can be constructed in a single column as shown in Fig. 7(b), replacing the whole process comprising three columns in the conventional system. Since offshore operation requires the compactness of equipment due to limited space and a harsh environment, the side-rectifier DWC is a good candidate for the LNG plant if the column operating pressure is properly selected. Due to the single operating pressure in the DWC, unlike the conventional system of multiple column pressures, the condenser temperature is lower than that of the conventional system and its reboiler temperature is higher. The in-tray heat exchangers can reduce the consumption of high cost utilities for the condenser and reboiler.

The side-rectifier DWC is compact, and its low pressure operation gives many benefits, such as low investment due to thin vessel wall, no formation of hydrates, and lower compression of the feed. The heating and cooling duties of the side-rectifier DWC are 5.9% and 5.1% less than those of the conventional system, respectively. The economic evaluation indicates that the side-rectifier DWC requires 57% less investment and 10% more utility cost than the conventional system. The low compression of the feed saves the compressor cost of 5.1 times the total plant investment, and the electricity cost of 1.8 times the total utility cost in the conventional system.

2. Control of Side-rectifier Divided Wall Columns [53]

The application of the common DWC in field operation has been successful for many years [8,73]; however, the operation of the

DWC is more difficult than the conventional distillation column. It is the main concern of the field operators considering DWC adoption. The operation of the side-rectifier DWC is expected to be similar to the DWC operation. The overhead product from the rectifier can be separately adjusted using the reflux flow to the rectifier. The gain of product mole fraction from the applied change of manipulated variables indicates that the conventional system shows the best control performance as explained in Wolff and Skogestad [35]. However, the performance of the rectifier DWC is better than that of the existing pre-column DWC [71].

3. Benzene Separation [74]

Benzene is a well-known carcinogen that has been avoided in many application fields of hydrocarbon products. The reformate from catalytic crackers is widely used as an octane booster in high-grade gasoline due to the high content of aromatic hydrocarbons; however, benzene has to be removed from the application due to environmental reasons. The new rule of a benzene limit in gasoline requires the reduction of benzene content in the blending reformate, a high octane blending component, obtained by catalytic reforming of naphtha and heavy oil [75,76]. The blended naphtha reformate provides approximately 75% of benzene present in gasoline [77]. On the other hand, benzene is an intermediate in the production of chemicals such as ethylbenzene, cumene, c-hexane, and alkylbenzene, which are feedstocks of many consumer products. Food grade *n*-hexane is used for the extraction of cooking oils from vegetable seeds, which is also separated from the naphtha containing the benzene. Therefore, benzene removal from the naphtha is also necessary in various applications [78]. Many benzene separation processes have been developed [79-82]. Benzene separation from hydrocarbon feedstock has been conducted through the extraction of aromatic compounds from the feedstock mixture, and the distillation of aromatic compounds. Later, extraction and distillation were combined to create extractive distillation [80, 83]. The close boiling points among the aromatic and non-aromatic compounds make the direct application of distillation to the separation by components difficult. Extraction separates the aromatic compounds from the non-aromatic compounds, and the aromatic compounds with large a difference in boiling points are separated by distillation. However, the extraction process uses a high-cost solvent, and its regeneration requires a large amount of high-cost utilities due to the high boiling point of the solvent.

When benzene alone is separated from the feedstock as used in the production of gasoline blend, the conventional process of separating all aromatic compounds together is not cost effective. Since the extraction process of all aromatics requires a high investment and operational costs, the extraction process of benzene alone gives a significant reduction in investment and operating cost. The extraction process is inefficient in terms of energy consumption. The large amount of recycled feed from the stripper and the high boiling point of the solvent require a large energy demand at a high cost. When benzene separation from the reformate is targeted for the use of gasoline blend, the extraction feedstock in the conventional process can be reduced by introducing a separation process before the extraction process, as illustrated in Fig. 8. The reduction in feedstock directly lowers the load of extraction process, requiring 72% of the total energy demand in the process.

The main difference between the conventional and proposed systems is the location of the benzene separation process [84]. In the proposed system, the process of benzene separation using the extended DWC [6,30,39,85-87] is placed before the extraction process. The feed components are classified into four groups by checking the distribution of the boiling points and the combination of non-aromatic and aromatic components. When a conventional distillation system is employed in group separation, three binary columns are necessary for the separation. In the separation of the benzene group only, however, the last column is not necessary because the separation of toluene and xylenes is not required. In the application of the extended DWC, which is more energy-efficient than the conventional system [80], the separation of toluene and xylene was not tight enough to reduce the energy requirement. The com-

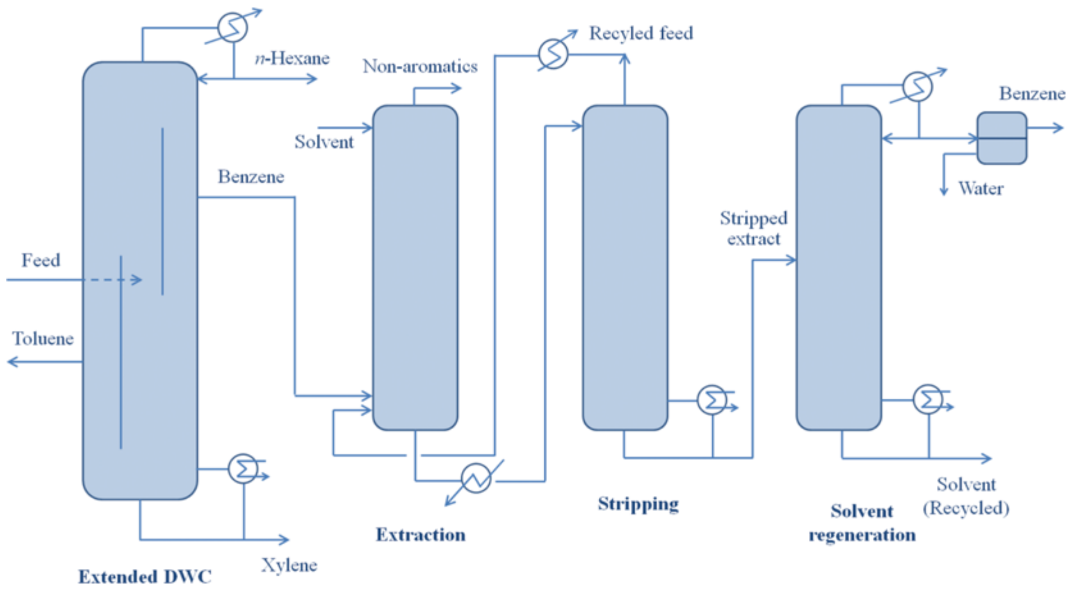


Fig. 8. Schematic diagram of the benzene removal process with an extended DWC [74,84].

puted results indicate that the proposed process saves 56.8% of the heating duty over the conventional process, and that of the cooling duty is 64.6%. The economic analysis shows that a 26% reduction in the investment cost and 56% reduction in the utility cost are yielded from the proposed process compared to the conventional system.

CONCLUSIONS

The design and control of the energy-efficient distillation columns, divided wall (DWC), diabatic distillation, and internally heat-integrated distillation (HIDiC) column, are briefly summarized here. Although many of the columns have been commercially implemented in field applications, their design and control have not been thoroughly investigated due to the perception of well-developed technology in distillation, and the availability of commercial design software. In the present review, general information regarding energy-efficient distillation columns was introduced, and three example applications to practical processes were presented. The applications indicate that the energy-efficient distillation column saves a significant amount of energy demand, and gives versatile configuration of the separation process, to meet the specific process requirements such as offshore application, improved controllability of DWC, and reduced extraction load.

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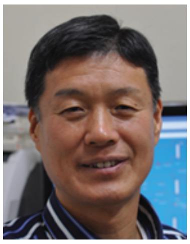

Young Han Kim is a Professor in the Department of Chemical Engineering at Dong-A University in Korea. He received his B.S. degree (Dong-A University, Korea), M.S. degree (KAIST, Korea), and D. Eng. degree (Lamar University) all in Chemical Engineering. He worked for a couple of years at the Korea Mint and Printing Agency before joining Dong-A University in 1980. He was a visiting professor at Lehigh University and the University of Tennessee at Knoxville. His research interest includes energy saving in separation processes.