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**Special Issue for the International Workshop on
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Preface to the Special Issue for IWPI 2012 Hiroshi Suzuki, Chongyoup Kim, Kwang Ho Song and Shunji Homma	85
Review of Retrofitting Distillation Columns Using Thermally Coupled Distillation Sequences and Dividing Wall Columns to Improve Energy Efficiency (Journal Review) Nguyen Van Duc Long and Moonyong Lee	87
Review of Visualization of Flow and Dispersion States of Slurry System Fluids in Stirred Vessels (Journal Review) Meguru Kaminoyama	109
Application of Taylor Vortex to Crystallization (Journal Review) Woo-Sik Kim	115
Process Development for Ultrasonic Fracturing of Zirconium Phosphate Particles Takafumi Horie, Shinsuke Akao, Takayuki Suzuki, Koki Tanaka, Ning Jia, Keita Taniya, Satoru Nishiyama and Naoto Ohmura	124
Preparation of Silica-Coated SnPt Bimetallic Nanoparticle Catalysts for the Selective Hydrogenation of Cinnamaldehyde Keita Taniya, Taiki Hara, Tomota Imai, Yuichi Ichihashi and Satoru Nishiyama	130
Intensification of Photochemical Wastewater Decolorization Process Using Microreactors Bruno Ramos, Shinichi Ookawara, Yoshihisa Matsushita and Shiro Yoshikawa	136
Emulsion Crystallization of Submicron Sized High Density Polyethylene Particles Using Micromixer Sang Hoon Park, Seo Young Kim, Kwang Ho Song and Jaehoon Choe	141
Power Consumption and Mixing Performance of an Eccentrically Located Maxblend Impeller Kazuhiko Nishi, Naoki Enya, Ryuta Misumi and Meguru Kaminoyama	146
Fluid Deformation Induced by a Rotationally Reciprocating Impeller Saki Senda, Yoshiyuki Komoda, Yushi Hirata, Hiroshi Takeda, Hiroshi Suzuki and Ruri Hidema	151
Enhancement of Dispersion of Silica Modified with a Silane Coupling Agent in a Rubber Composite Gyu Min Lee, Jung Whan Yoo and Ki Bong Lee	159
Rheology of Silica Sols/Gels Obtained by a Y-Shaped Reactor with a Dilute Method Aya Kaide and Takashi Saeki	165
Phase Separation Characteristics of Ammonium Alum Hydrates with Poly Vinyl Alcohol Ruri Hidema, Takuya Tano, Hiroshi Suzuki, Makoto Fujii, Yoshiyuki Komoda and Takafumi Toyoda	169
Application of a Drag Reduction Phenomenon Caused by Surfactant Solutions Takashi Saeki	175



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Layer-by-Layer Assembly of Inorganic Nanosheets and Polyelectrolytes for Reverse Osmosis Composite Membranes	
Jungkyu Choi, Hyemin Sung, Yongmin Ko, Seunghye Lee, Wanseok Choi, Joona Bang and Jinhan Cho	180
A Framework for Application of Genetic Algorithm to Model-Based Design of Reactive Distillation Process	
Kai Tun Lim, Hideyuki Matsumoto, Takehiro Yamaki and Keigo Matsuda	187
Computations of Compound Droplet Formation from a Co-axial Dual Nozzle by a Three-Fluid Front-Tracking Method	
Shunji Homma, Kouta Moriguchi, Taeseon Kim and Jiro Koga	195
Flow and Oxygen-Dissolution Characteristics of Microbubbles in a Viscoelastic Fluid	
Hiroshi Suzuki, Yuto Furukawa, Ruri Hidema and Yoshiyuki Komoda	201
Parametric Study of Periodic Temperature Cycling Using Microreactor (SC)	
Makoto Sakurai, Hiroki Oku and Hideo Kameyama	207

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Review of Retrofitting Distillation Columns Using Thermally Coupled Distillation Sequences and Dividing Wall Columns to Improve Energy Efficiency

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Keywords: Debottlenecking, Dividing Wall Column, Process Integration, Process Intensification, Retrofit, Thermally Coupled Distillation Column

Distillation is a common energy-intensive process. Accordingly, it is the first process to be addressed to improve the energy efficiency over both the short- and long-term. Recent studies and industrial applications have proven that advanced process integration and process intensification techniques such as the use of a thermally coupled distillation sequence (TCDS) and a dividing wall column (DWC) require the lowest amount of energy for the separation of mixtures into pure product streams. This paper reviews some energy-efficient distillation technologies that can be used in a retrofit design. The research on and implementation of retrofits using a TCDS and DWC are reviewed. This report proposes coupled schemes as alternatives to using a Petlyuk column that do not have the classical problem of controlling the vapor transfer from one column to another and have not previously been proposed for retrofits. These schemes are expected to make significant contributions to improving the energy efficiency and mitigating CO₂ emission in the retrofitting of distillation systems. The authors evaluated a solution for retrofitting azeotropic and extractive distillation systems. Various issues such as the constraints, techno-economic analysis, controllability, and operability are discussed briefly to provide more insight into the application of TCDS and DWC technologies in the retrofit.

Introduction

Distillation, a thermal separation method, is one of the most important separation technologies in the chemical processing industry. Nevertheless, despite its many well-known advantages and widespread use, its significant energy requirements are a major drawback, because distillation can generate more than 50% of the plant operating cost (Kiss and Bildea, 2011). Furthermore, saving energy in this area has become an important issue from an environmental or CO₂-mitigation standpoint, because the huge amount of energy consumed in the distillation has a large impact on greenhouse gas emissions (Matsuda *et al.*, 2012). One innovative solution for reducing the total annualized cost (TAC), which includes both operating and capital costs, is the use of advanced process-integration and process-intensification techniques, such as the implementation of a thermally coupled distillation sequence (TCDS) and a dividing wall column (DWC) (Tedder and Rudd, 1978a, 1978b, 1978c; Fidkowski and Królikowski, 1986, 1987, 1990; Kaibel, 1987; Triantafyllou and Smith, 1992; Kim, 2002; Olujić *et al.*, 2003; Hwang *et al.*, 2008; Olujić *et al.*, 2008, 2009; Asprien and Kaibel, 2010; Long and Lee, 2012a). In particular, a DWC is one of the best examples of a proven process intensification technology in distillation, because it has significantly

lower investment and operating costs while also reducing the amount of equipment required and the carbon footprint (Kiss and Suszwalak, 2012). According to Schultz *et al.* (2002), the DWC will become a standard distillation tool in the next 50 years, with an estimated 350 industrial applications by 2015 (Yildirim *et al.*, 2011).

Retrofits of distillation systems focus on the more efficient reuse of existing equipment to increase profit. When carrying out a retrofit study, retrofit models are essential for fixing the existing distillation design. The most straightforward designs are grass-roots designs, because they allow the most freedom to choose the design options and size of the equipment. The design of a retrofit must attempt to work within the constraints of existing equipment (Smith, 2005). The retrofit of distillation columns is carried out more often than the installation of new equipment, because distillation is an energy-intensive process that requires considerable capital investment (Gadalla *et al.*, 2003). Retrofit projects comprised 70–80% of capital investment projects in the processing industry at the end of the 1980s (Liu and Jobson, 2004a).

Two main approaches are adopted for the design of distillation system retrofits to increase the throughput (Liu and Jobson, 2004a):

- (1) replacing existing internals with high-capacity and/or high-efficiency internals and
- (2) revamping the process by improving the utilization of existing equipment and making relatively minor modifications, including adjusting the operating conditions, adding equipment, etc.

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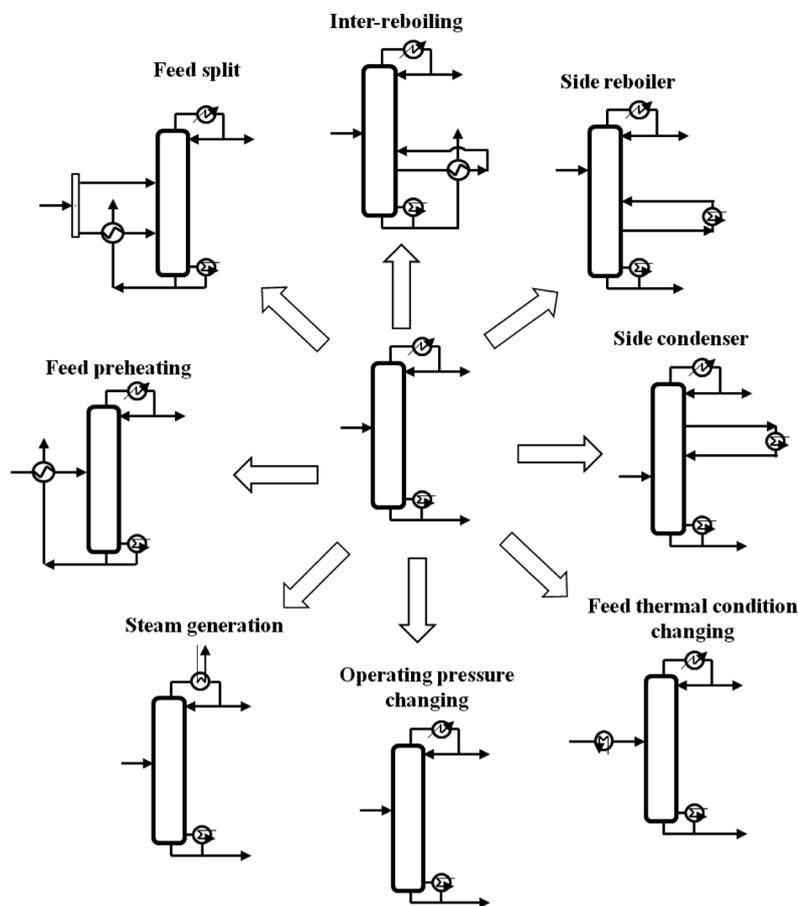


Fig. 1 Promising technologies for the retrofit of a single column

Most distillation retrofit practices emphasize column internals that not only promote separation, but also govern the column hydraulic performance (Amminudin and Smith, 2001). The retrofit of existing columns, such as the replacement of existing trays or packings with effective alternatives, is a frequent option because the user companies strive to increase production with minimum investment. Currently, vacuum applications are dominated by structured packings, whereas trays are normally used in high-pressure applications (above 5 bar; Olujić *et al.*, 2009). In addition, random packings can find favorable applications in the complete operating range. To cope with the ever growing demand for capacity, all three families of vapor–liquid contactors have been subjected to intensive research and development in recent years (Schultes, 2003; Kashani *et al.*, 2005; Weiland *et al.*, 2005; Jödecke *et al.*, 2006, 2007; Olujić, 2007; Penciak *et al.*, 2006; Darakchiev and Semkov, 2008). One excellent review (Olujić *et al.*, 2009) provided a comprehensive overview of the equipment trends in distillation covering current column internals. On the other hand, the use of better internals in retrofitted distillation columns is not the only design option, nor is it always the most cost effective (Liu and Jobson, 2004a). In some cases, this does not improve the energy efficiency of the system and can subsequently prevent a large increase in capacity (Manley, 1998b). Furthermore, in the case where the column already has a high-efficiency

internal, the potential for increasing the capacity by replacing the existing column internal with a new one is limited. This paper focuses on revamping the process to improve the utilization of existing equipment and making relatively minor modifications, including adjusting the operating conditions, adding equipment, and rearranging the existing columns into a complex sequence.

Most research and review papers published thus far focused on new designs of TCDSs and DWCs. An excellent review (Dejanović *et al.*, 2010) gives a comprehensive overview of DWCs covering both the theoretical description and patent area, whereas another excellent review (Yildirim *et al.*, 2011) examined the current industrial applications of DWCs and related research activities, including column configuration, design, modeling, and control issues. Furthermore, the applications of DWCs for azeotropic, extractive, and reactive distillation were highlighted. The present paper provides a complete overview of promising retrofit design options for distillation systems including single- and multiple-column cases. The work focuses on design options that increase the effectiveness while utilizing the existing shells and internals, rather than simply replacing the internals. This paper also reviews the research on and implementation of retrofits using process integration, TCDSs, and DWCs. Coupled schemes were proposed as alternatives to using a Petlyuk column to improve the energy efficiency in

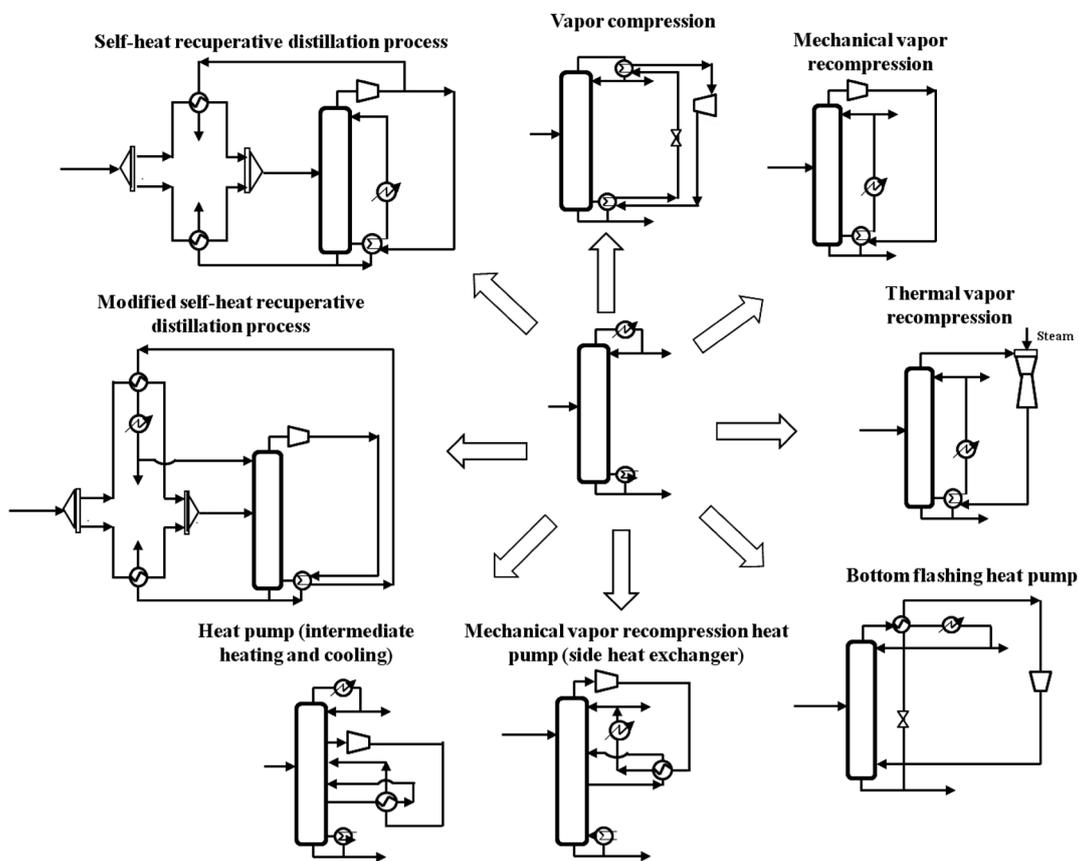


Fig. 1 Promising technologies for the retrofit of a single column (continued)

a retrofit. Furthermore, the authors examined a solution for the retrofit of azeotropic and extractive distillation. Finally, the constraints, technical analysis, economic analysis, controllability, and operability in the retrofit are discussed briefly.

1. Promising Column Configurations for Retrofits

1.1 Single-column case

To improve the energy efficiency, the heat integration concept was first introduced approximately 70 years ago (Jana, 2010). The basic idea of the heat integration approach is that the hot process streams are heat-exchanged with cold process streams. **Figure 1** shows promising technologies for the retrofit of a single column, such as a heat pump, self-heat recuperation technology, feed splitting and feed preheating, inter-reboiling, a side reboiler or a side condenser, changing the thermal conditions of the feed, and changing the operating pressure.

1.1.1 Heat pump Distillation has relatively low thermodynamic efficiency (Kim, 2012; Kiss *et al.*, 2012), requiring the input of high-quality energy in the reboiler to perform a separation task. At the same time, a similar amount of heat at a lower temperature is given off in the condenser. Several heat pump concepts have been proposed to improve the energy efficiency of distillation columns. The vapor compression (VC) heat pump uses a working fluid that is

evaporated at the condenser, compressed to a higher (saturation) temperature, condensed in the reboiler, and cooled by expansion over a throttle valve to a (saturation) temperature below the condenser temperature (Bruinsma and Spoelstra, 2010). The choice of working fluid is an important degree of freedom in the design. An industrial example of VC is the ethylene–ethane separation using propylene as the working fluid (Zimmerman and Walzl, 2009). In cases in which the distillate vapor cannot be compressed, VC is the only option in some novel heat pump systems. In addition, VC is particularly beneficial when dealing with corrosive and fouling compounds (Göktun, 1995).

The mechanical vapor recompression (MVR) heat pump is applied widely to the separation of mixtures with similar boiling points. The overhead vapor is pressurized using a compressor to such a level that it can be condensed at a higher temperature to supply sufficient heat to the reboiler. This leads to a major decrease in the energy requirements of the reboiler and condenser (Moser and Schnitzer, 1985; Ranade and Chao, 1990; Mizsey and Fonyo, 1992; Annakou and Mizsey, 1995; Long and Lee, 2013a). The use of mechanical compression as a heat pump is economical mainly for separating low-relative-volatility mixtures, where small compression ratios and consequently small compressor duties are required because of the small temperature difference between the top and bottom of the column (De Rijke, 2007). The advantages of this technique over VC are that the

condenser in a MVR heat pump is smaller and that the temperature increase is approximately 5 K lower, because heat is exchanged only once. This results in higher thermodynamic efficiency (Bruinsma and Spoelstra, 2010).

The thermal vapor recompression (TVR) heat pump is a variant of the MVR heat pump in which the compressor is replaced by a steam ejector as the work input mechanism (Kiss *et al.*, 2012). TVR has been implemented widely in industry because of the advantages of the steam ejector (Feng and Berntsson, 1997). The steam ejector uses the Venturi effect to obtain mechanical energy from steam injection into a special variable-diameter pipeline. This makes TVR a robust design with reduced capital and maintenance expenditure, because there are no rotating pieces involved (Fonyo and Benkő, 1998; Perry and Green, 1999; Kiss *et al.*, 2012). On the other hand, the input steam is mixed with the distillate to generate the required pressure, so TVR is used mostly for systems producing water as the top product (Chen and Sun, 1997).

In a bottom flashing heat pump, the bottom stream from the column is divided into two streams: the final product stream and another that is expanded by a valve to decrease its temperature and allow heat exchange with the top stream before being recompressed to the column pressure (Fonyo *et al.*, 1995; Long and Lee, 2013a). Fonyo *et al.* (1995) used this system to separate *i*-C₄ and *n*-C₄, whereas Long and Lee (2013a) combined this technique with a bottom dividing wall column (BDWC) to integrate the debutanizer and deisobutanizer and reported remarkable energy savings.

1.1.2 Self-heat recuperation technology In heat pumps, only the heat recovery duty of the reboiler in the distillation column has been considered extensively, while the fate of the heat introduced during preheating has not been well recognized. In contrast, self-heat recuperation technology uses both latent and sensible heat in the process through the use of a compressor (Kansha *et al.*, 2009, 2013; Matsuda *et al.*, 2011a). Recently, Kansha *et al.* (2010) developed a novel integrated process module based on self-heat recuperation that facilitated heat circulation for use in distillation processes. By dividing the distillation processes among two modules, i.e., heat circulation and distillation modules, the heat of condensation and the cooling heat were recuperated by compressors and exchanged with the heat of vaporization and the heating heat through the use of heat exchangers in each module, without additional heat. This self-heat recuperation technology facilitates the recirculation of both latent and sensible heat in a process and helps reduce the energy consumption of that process through the use of compressors and self-heat exchangers (Kansha *et al.*, 2010).

This technology can be used not only in grass-roots cases, but also in retrofit cases, and it has been considered in a range of processing industries (Long and Lee, 2013c). This is a promising technology when the problem is associated with binary mixture separation or when the column should not be integrated with other columns in sequence. With the existing column, new heat exchangers and compressors can be installed, while the number of trays and the diameter of the

column are fixed. More pipe work will also be needed for the equipment links. From a technique point of view, these studies can be accomplished easily in a short modification time.

1.1.3 Feed splitting and feed preheating The thermal conditions of the feed can be altered to reduce the reboiler duty through heat exchange with the bottom product or with any other low-grade heat sources available. The efficiency associated with using feed preheating to provide a portion of the thermal energy given to the feed reduces the reboiler duty (Liebert, 1993; Deshmukh *et al.*, 2005). Splitting the feed into two streams and preheating only one fraction of the feed stream makes it possible to improve the feed preheating efficiency up to 100% (Wankat and Kessler, 1993; Fidkowski and Agrawal, 1995). Soave and Feliu (2002) proposed the use of a steady-state simulator to determine iteratively the appropriate split fraction to save energy (up to 50%) in industrial distillation towers.

1.1.4 Inter-reboiling To minimize energy consumption, the bottom liquid product can be subcooled while inter-reboiling the bottom section of the column (Manley, 1998a; Long and Lee, 2012b). Manley applied inter-reboiling to improve the natural gas liquid recovery (NGL) performance, particularly to the deethanizer and depropanizer. This heat effect is particularly significant when the feed contains significant amounts of heavy components such as butanes and gasoline in the feed to a conventional NGL deethanizer distillation column. The draw and return stages for a partial inter-reboiler are on the same stage. Compared to an NGL deethanizer without an inter-reboiler, the system with inter-reboiling can reduce the hot utility by 26%. Manley also found that the draw temperature can be significantly reduced by requiring more theoretical stages than disclosed between the inter-reboiler draw and return stages. Increasing the number of stages between the draw and return stages reduces the temperature to which the hot bottom product may be cooled, increases the inter-reboiler duty, and reduces the reboiler duty.

1.1.5 Side reboiler or side condenser Thermal integration of a distillation column through the use of side exchangers also improves the exergetic efficiency of the column (Bandyopadhyay, 2007). For subambient distillation, a significant decrease in energy consumption can be achieved by incorporating side condensers and side reboilers (Lynd and Grethlein, 1986; Kleinberg, 1987; Aguirre *et al.*, 1997).

The use of a side reboiler or side cooler can also allow the throughput of a distillation column to increase (Liu and Jobson, 2004b). Side reboilers and side coolers can be used to change the vapor and liquid flows within a column section to utilize the area available more uniformly. The liquid and vapor traffic in the bottommost section of the column can be reduced using a side reboiler, and the traffic to the underutilized stages between the side-reboiler and feed will increase. Therefore, this process modification increases the uniformity of area utilization throughout the column section. A side reboiler will reduce the vapor and liquid traffic below the tray where the side reboiler is placed and increase

the vapor and liquid traffic above the tray. Similarly, a side cooler will reduce the vapor and liquid traffic on the trays above it and increase the vapor and liquid traffic below it.

1.1.6 Changing the feed thermal conditions The thermal conditions of the feed have a strong influence (Liu and Jobson, 2004b) on the processing capacity of an existing distillation column. This is particularly true for columns performing difficult separations. This discussion focuses on distillation columns with a single feed and only two products, but the ideas can also be applied to more complex columns.

A methanol plant that utilizes two distillation columns to purify methanol in its separation section was retrofitted (Demirel, 2006). The suggested retrofits consisted of an additional side condenser at stage 4 and feed preheating for column 1, as well as two side reboilers at stages 87 and 92 for column 2. The effectiveness of the retrofits was assessed using the improved column grand composite curves and exergy loss profiles as well as by performing an approximate economic analysis. After the retrofits, the actual and minimum vapor flow profiles became closer. In addition, the difference between the ideal and actual profiles of the enthalpies in the columns' grand composite curves decreased. The reductions in the total exergy losses ranged from 21.5 to 41.3%, which resulted in considerable savings in the available energy losses. The thermodynamic efficiencies also increased considerably. Therefore, the columns operate with fewer thermodynamic imperfections.

1.1.7 Changing the operating pressure In a retrofit design, design engineers often want to increase the throughput of an existing distillation column. Among the operating parameters, pressure is very important (Liu and Jobson, 1999). The operating pressure has a complex influence on the distillation performance; it affects the relative volatility between the components, molar vapor flow rates, flooding limitations, and vapor density.

Many studies have reported that increasing the pressure can decrease the diameter of a distillation column for a given separation (Liu and Jobson, 1999). Winkle (1967) stated that the vapor volume increases with decreasing pressure, and larger-diameter columns are needed to handle the increase in vapor volume. This increase in column size increases the investment cost. Kister (1992) reported that one of the favorable effects of increasing the column pressure is that it increases the vapor density and vapor handling capacity. This leads to major decreases in the column diameter and capital cost under vacuum, as well as to smaller reductions up to pressures of 50 to 150 psia (3.4 to 10.2 bar). Humphrey and Keller (1997) suggested that at higher pressures and temperatures, the vapor pressures increase and the viscosities decrease, which leads to higher efficiency and vapor capacity as well as a lower column diameter.

Other studies reported that decreasing the pressure can increase the capacity of a distillation column (Liu and Jobson, 1999). Capps (1993) found that for high-pressure systems, a decrease in the operating pressure allows an increase in the feed rate. This occurs because the relative

volatility and flooding capacity increase. Castillo and Dhole (1995) examined the ethylene cold-end process and suggested that the throughput of the columns in the process could be increased when the operating pressure of the demethanizer was decreased from 3,500 to 3,100 kPa.

Liu and Jobson (1999) provided a clear and quantitative picture of the effect of pressure on the throughput of an existing distillation column. When the operating pressure is less than approximately 3 bar, increasing the pressure can increase the throughput of the existing column. When pressure is greater than approximately 7 bar, a decrease in the pressure can increase the throughput. Moreover, when the pressure is in an intermediate range, pressure changes have little effect on the throughput.

1.2 Multiple-column case

Currently, process intensification is considered the main trend for improving process performance. Process intensification aims to reduce the number of equipment units through the innovative design of multifunctional equipment, leading to reduced investment cost and significant energy savings (Rong and Turunen, 2006). For a distillation system, the thermal coupling technique provides a new mechanism for retrofitting the traditional simple column configuration through the principle of process intensification (Errico *et al.*, 2007). This occurs through the elimination of the condenser, reboiler, or both in the traditional simple column configuration using thermal coupling to provide simultaneous mass and heat transfer between the different tasks in the separation sequence. Therefore, the thermal coupling technique provides a unique approach for intensifying the traditional simple column configuration and has several advantages: a) a decrease in the number of the heat exchangers, b) an improved separation efficiency, and c) the potential to save both energy and capital costs.

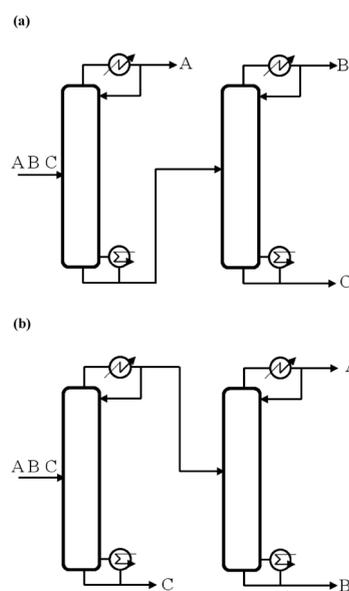


Fig. 2 Schematic diagram of the (a) direct sequence and (b) indirect sequence

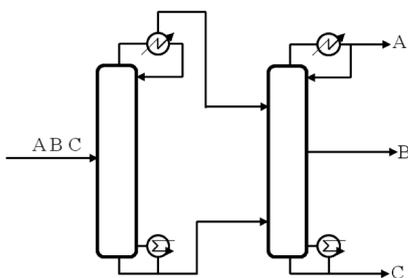


Fig. 3 Schematic diagram of the prefractionator arrangement

1.2.1 Prefractionator arrangement The direct and indirect conventional distillation sequences for ternary distillation can be employed to separate a three-component feed into the pure products, as illustrated in **Figures 2(a)** and **(b)**, respectively. Every distillation column has a reboiler and a condenser. The number of product flows in the columns is always the same, two. On the other hand, in a more novel distillation scheme, i.e., in a prefractionator scheme, as illustrated in **Figure 3**, there is one extra product flow, which is known as a side stream, in the second column of the column sequence (Malinen and Tanskanen, 2009). This prefractionator arrangement allows improved control and operation, since control of the external flows from the reboiler and condenser of the prefractionator column is facile. The prefractionator configuration is advantageous for conventional distillation schemes and provides better energy performance (Amminudin and Smith, 2001; Poth *et al.*, 2004).

1.2.2 Side stripper or side rectifier and Petlyuk column A TCDS can be built by implementing two interconnecting streams (one in the vapor phase and the other in the liquid phase) between the two columns. Such systems have been studied for the separation of ternary mixtures and have been shown to provide significant energy savings with respect to both the conventional direct and indirect distillation sequences. The three most widely analyzed thermally coupled systems are the sequence with a side rectifier, the sequence with a side stripper, and a fully thermally coupled system (or Petlyuk column), which are illustrated in **Figures 4(a)**, **(b)**, and **5**, respectively (Glinos *et al.*, 1986; Fidkowski and Królikowski, 1990; Triantafyllou and Smith, 1992; Hernández and Jiménez, 1996; Jiménez *et al.*, 2003).

Of the above possible thermal coupling arrangements, the side stripper and side rectifier have been used widely in refinery distillation and cryogenic air separation, respectively (Seidel, 1935; Watkins, 1979; Amminudin *et al.*, 2001). The Petlyuk column provides a fully interconnected structure with two thermal couplings that result in vapor interconnections flowing back and forth between the columns (Hernández *et al.*, 2005). These sequences provide energy savings of up to 30% over the conventional direct and indirect distillation sequences (Tedder and Rudd, 1978a; Alatiqi and Luyben, 1985; Triantafyllou and Smith, 1992; Finn, 1993; Hernández and Jiménez, 1996; Hernández and A. Jiménez, 1999; Blancarte-Palacios *et al.*, 2003).

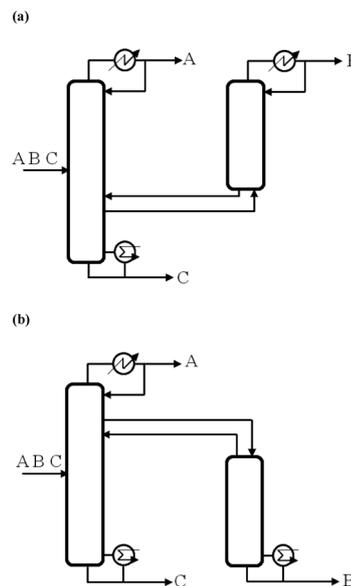


Fig. 4 Schematic diagram of the thermally coupled distillation sequences: (a) system with side rectifier and (b) system with side stripper

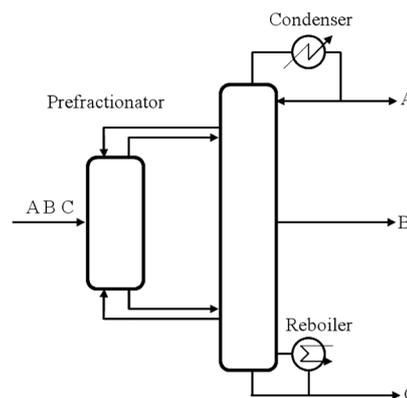


Fig. 5 Schematic diagram of the Petlyuk column

1.2.3 Coupled schemes as alternatives to using a Petlyuk column Recently, Agrawal and Fidkowski (1998, 1999) proposed six alternative coupled schemes (**Figure 6**) that might provide better operating properties than just the Petlyuk column. In particular, the Petlyuk system includes a vapor stream that passes from the first column (or prefractionator) to the main column and another that moves in the opposite direction. This requires that the pressure at the bottom of the prefractionator be lower than that of the main column, whereas the pressure at the top should be higher than that of the main column (Agrawal, 1999), which is difficult to control. The six alternative distillation schemes show interesting potential in terms of their energy efficiency (Jiménez *et al.*, 2003; Hernández *et al.*, 2006). In retrofit projects, savings should be considered, but operability is also an important factor. These alternative distillation schemes, which do not have the classical problem of controlling the vapor transfer from one column to another, can be used in a retrofit.

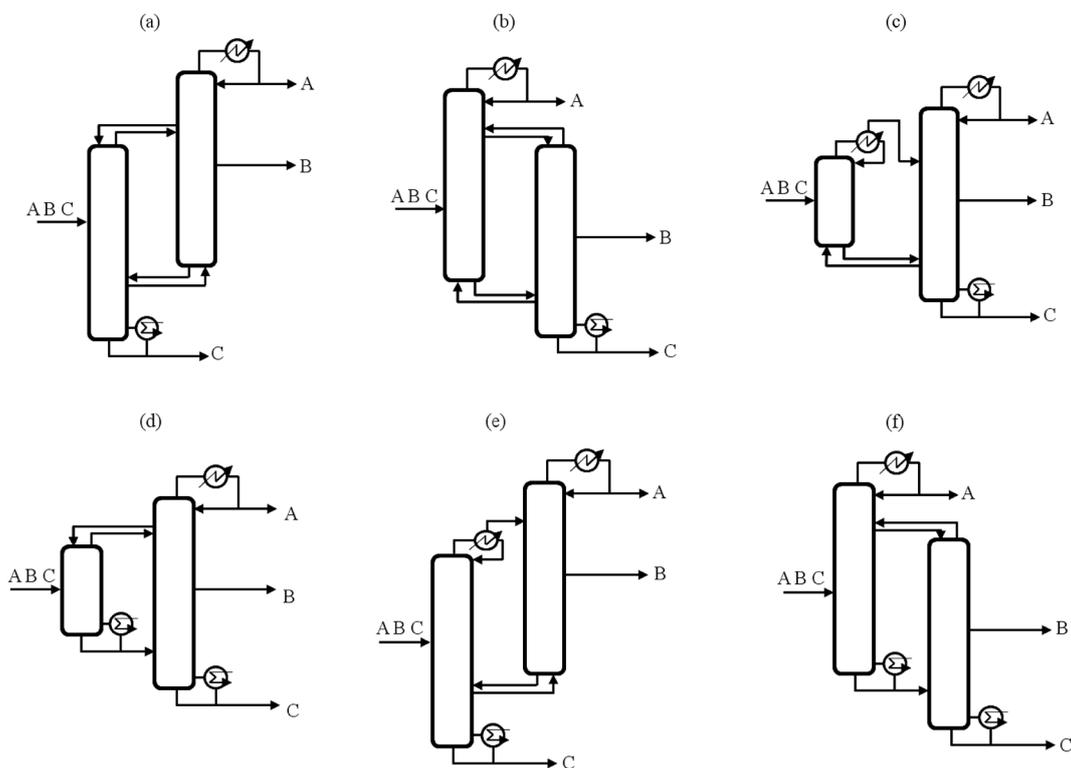


Fig. 6 Schematic diagram of coupled schemes as alternatives to using a Petlyuk column

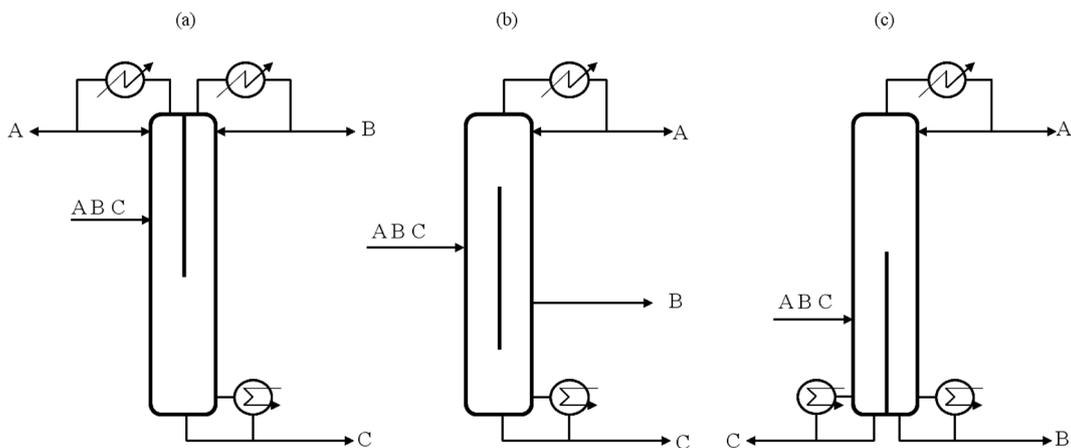


Fig. 7 Schematic diagram of the (a) TDWC, (b) DWC, and (c) BDWC

1.2.4 Dividing wall column In the first approach, a vertical wall is installed in the central section of the column, dividing it into a prefractionator and main section, as shown in **Figure 7**. This arrangement is referred to as the DWC, which is conceptually the same as the Petlyuk column given their thermodynamically equivalent arrangements (Amminudin *et al.*, 2001). A top dividing wall column (TDWC) or bottom dividing wall column (BDWC) can be implemented by moving the dividing wall to the top or bottom of the column, respectively. The DWC can effectively reduce the energy requirement by up to 30%, while also lowering the engineering and hardware costs compared to those of conventional direct and indirect distillation sequences

(Triantafyllou and Smith, 1992; Hernández and Jiménez, 1999; Segovia-Hernández *et al.*, 2007; Sotudeh and Shahraki, 2008; Tamayo-Galván *et al.*, 2008; Errico *et al.*, 2009; van Diggelen *et al.*, 2010; Long *et al.*, 2010; Kiss and Bildea, 2011; Kiss and Rewagad, 2011). This improved energy efficiency arises because DWCs can allow reversible splits with no part of the separation performed twice (Poth *et al.*, 2004). Although DWC has many benefits, it also has some limitations. For example, it is less appropriate when there is a large temperature difference between the reboiler and condenser, heat transfer across the dividing wall, or highly non-ideal behavior of the mixture, in which cases conventional or other configurations could be better suited.

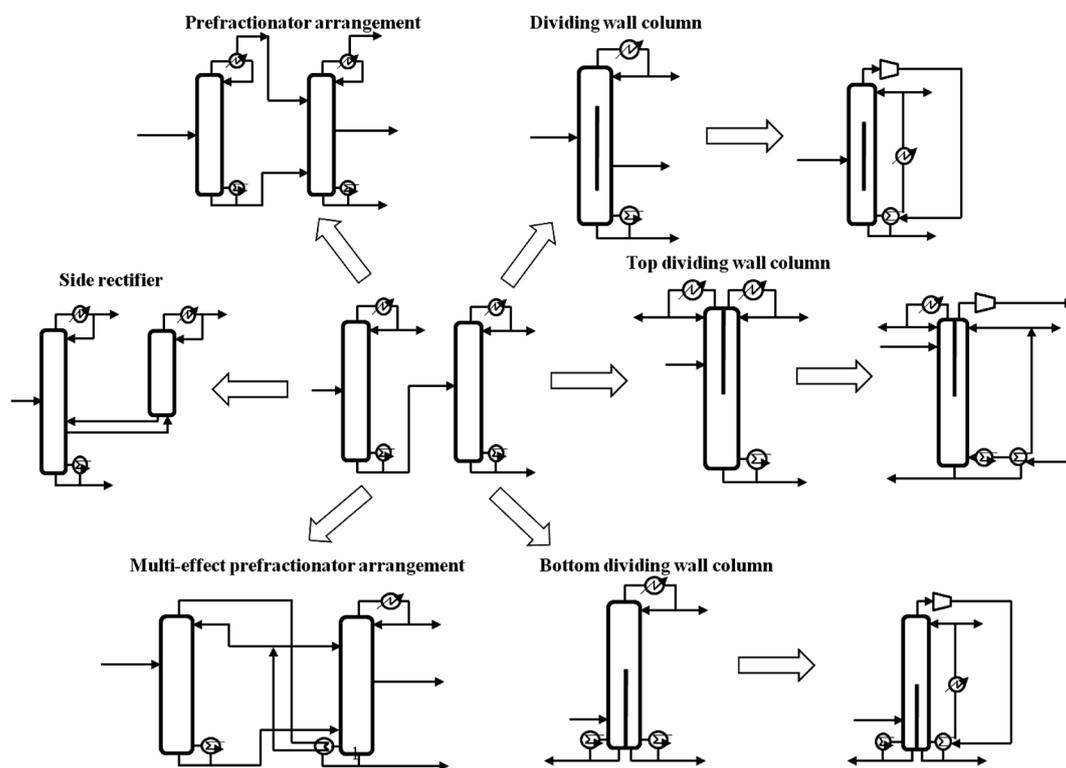


Fig. 8 Promising technologies for multiple-column systems (grass-roots design)

Interestingly, more than 10 years after the first use of a DWC at BASF in 1985, other companies realized that making adequate provisions for the separation of a three-component feed into pure products within a single shell, where appropriate, enables savings of both operating and investment costs (Olujic *et al.*, 2009). The reasons why these companies hesitated to use a DWC are many. The design of a DWC adds additional complexity (Slade *et al.*, 2006), since DWC design is more complex than the design of conventional arrangements because of the larger number of degrees of freedom that interact with each other and need to be optimized simultaneously, which makes optimization difficult and time consuming. A further restraint is the perceived complexity and uncertainty of the control system. On the other hand, the design is far less daunting with the relatively low-cost availability of computers and simulation packages. In addition, these issues with the control system have been mitigated by modern computerized control systems. The time available for revamp work might be one reason for avoiding a DWC. On the other hand, significant advances have been made in this area, as pointed out by Slade *et al.* (2006). A DWC was implemented successfully and on schedule by Koch-Glitsch in 30 d during May 2005. More applications are expected, particularly as the value of energy-conservation projects increases. Currently, there are more than 100 DWCs, and their number has been increasing rapidly (Harmsen, 2010). These are mainly new designs, but the number of projects revamping existing columns will increase with time (Dejanović *et al.*, 2010).

DWC is one of the best examples of a proven process in-

tensification technology in distillation (Kiss and Suszwalak, 2012). Therefore, most promising technologies for multi-component mixture separation systems are related to the use of a DWC in grass-roots cases (Figure 8). On the other hand, for retrofit purposes, implementing a DWC might have some possible complications associated with installing the dividing wall into the existing column, the possibility of requiring a larger column shell, and the longer downtime incurred (Amminudin and Smith, 2001). In that case, there are other options, such as coupled schemes as alternatives to using the Petlyuk or the prefractionator arrangements, which meet the retrofit objectives to exploit the existing columns and minimize the need for other units, as shown in Figure 9.

1.2.5 Combination of internal and external heat integration Interestingly, the incorporation of a heat pump into the BDWC, which includes internal and external heat integration, offers a very attractive option for improving the energy savings in the NGL process (Long and Lee, 2013a). BDWCs with top vapor recompression and a partial bottom flashing heat pump showed 36.65% and 26.04% decreases in energy consumption, respectively, compared to the conventional column sequence. This benefit can increase when the electricity/steam cost ratio is reduced or when the system is used in a country/company with cheap electricity. Based on this study, such a combination of internal and external heat integration can be further expanded to retrofits. In particular, incorporating a heat pump or self-heat recuperation technology into the retrofitted TCDS or retrofitted DWC can offer an impressive option to improve energy savings.

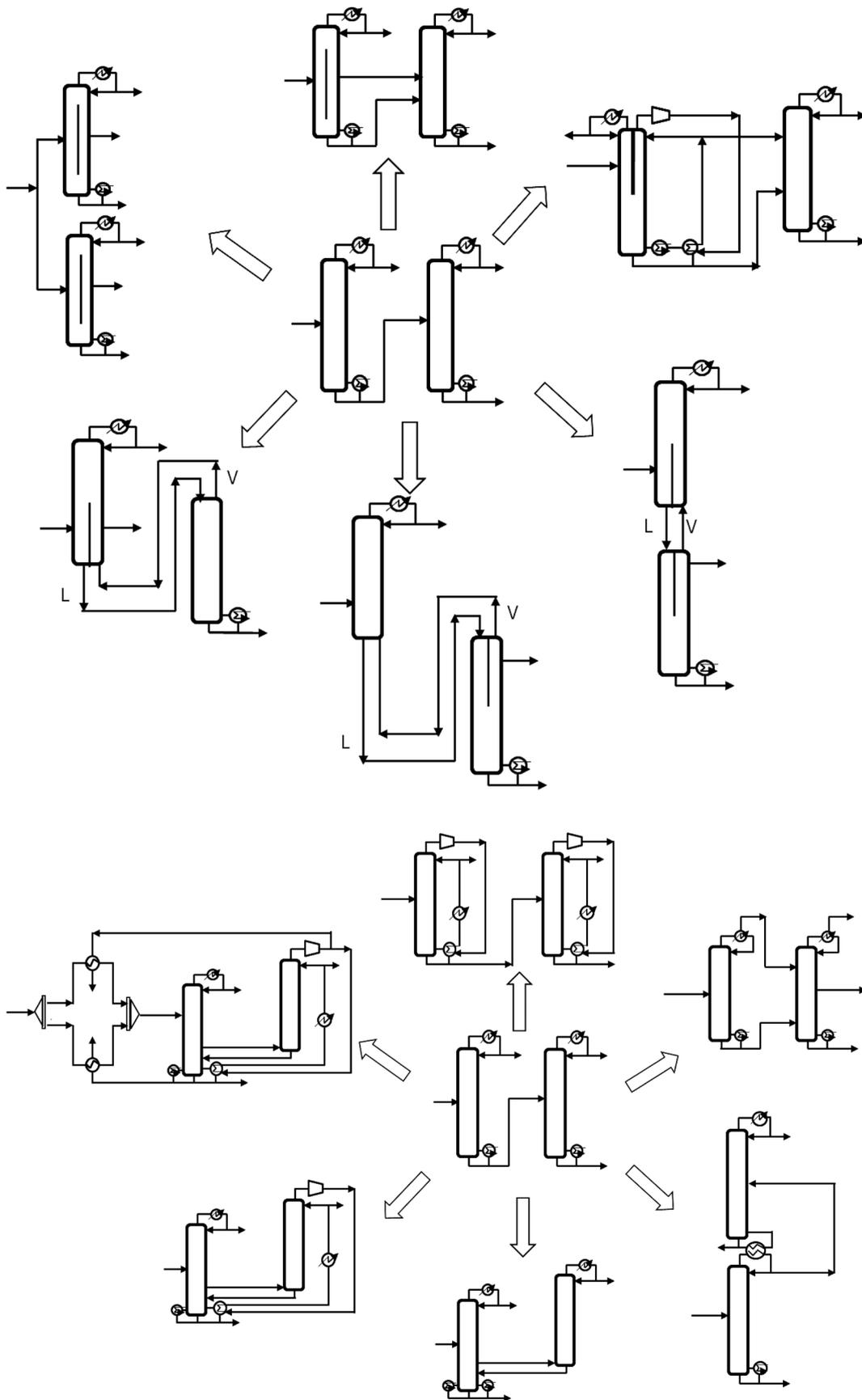


Fig. 9 Promising technologies for the retrofit of multiple-column systems

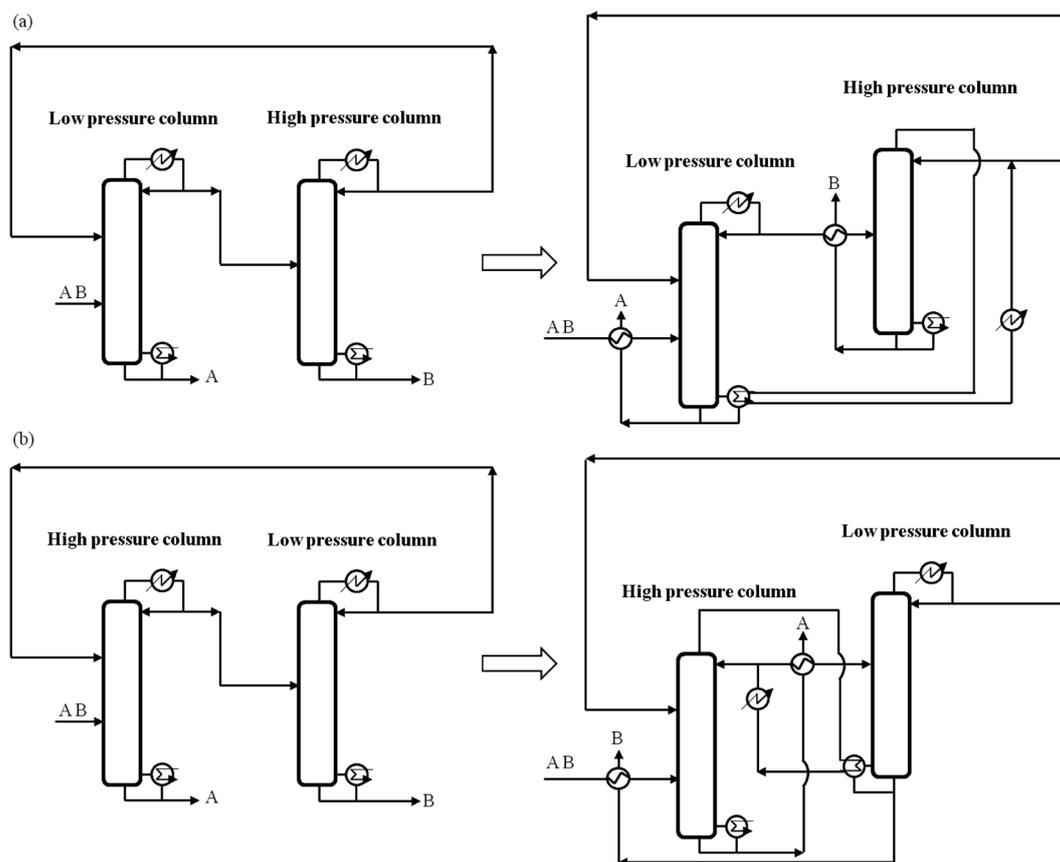


Fig. 10 Schematic diagram of pressure-swing azeotropic distillation and retrofitted pressure-swing azeotropic distillation

1.3 Azeotropic mixture

1.3.1 Pressure-swing azeotropic distillation Azeotropic and close-boiling components are commonly encountered in fine-chemical and specialty industries. Minimum-boiling azeotropes appear when there is molecular repulsion between different types of chemical components, which is more common than molecular attractions, which result in maximum-boiling azeotropes (Luyben, 2008a). The separation of these mixtures is a challenging task in many chemical processes and is impossible using a single conventional distillation column. Many non-conventional distillation techniques have been proposed to solve this problem (Widagdo and Seider, 1996; Doherty and Malone, 2001; Hamad and Dunn, 2002; Guedes *et al.*, 2007; Gutiérrez-Guerra *et al.*, 2009). The most common alternatives involve changing the operating pressure or adding a separation solvent.

Pressure swings can be used in some systems for separating homogeneous binary azeotropes whose azeotropic compositions change significantly with pressure (Luyben and Chien, 2011). When this occurs, a two-column sequence can be used to achieve the desired separation, as shown in **Figure 10**. The basic idea is to operate one column at low pressure and another column at high pressure. As shown in Figure 10(a), one of the components comes out from one end of the low-pressure column. If the azeotrope is minimum boiling, it will exit from the top and the product

stream will exit from the bottom. The composition of this distillate stream will be close to that of the azeotrope at low pressure. If the azeotrope is maximum boiling, the azeotrope and product stream will come out of the bottom and top, respectively (Luyben and Chien, 2011). The azeotrope is then fed to the second high-pressure column, in which similar separation occurs. This azeotropic stream is fed back to the low-pressure column (Knapp and Doherty, 1992; Luyben, 2005; Luyben, 2008a; Luyben, 2008b; Wang *et al.*, 2010; Yu *et al.*, 2012).

The reflux-drum temperature of the high-pressure column is higher than the base temperature of the low-pressure column, so heat integration can be attractive in terms of energy consumption (Luyben, 2008c). Abu-Eishah and Luyben (1985) determined the optimum design of a heat-integrated two-column system by minimizing the total energy consumption (the sum of the two reboiler duties). They then used the heat removed in the condenser of the high-pressure column as a portion (approximately 60%) of the heat input to the base of the low-pressure column. The remaining heat was provided by an auxiliary reboiler, which was heated by low-pressure steam. The reboiler in the high-pressure column was driven by high-pressure steam. Furthermore, a partially heat-integrated system was studied. The auxiliary reboiler provided an additional control degree of freedom, so both the tray temperature and reflux ratio could be manipulated independently in each column. A more than 50%

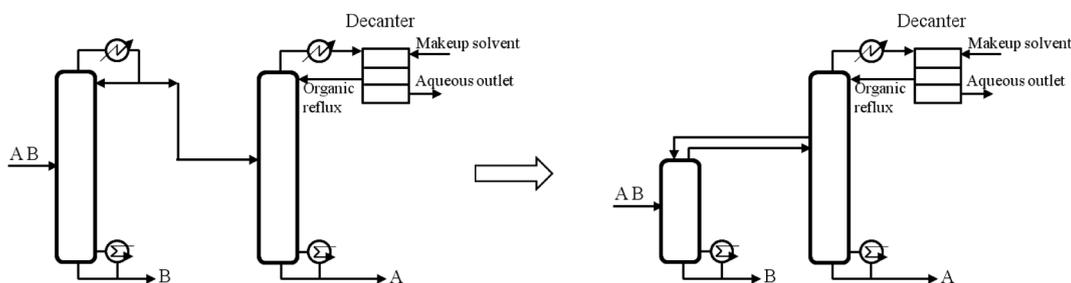


Fig. 11 Schematic diagram of azeotropic distillation and the proposed TCADS-SS

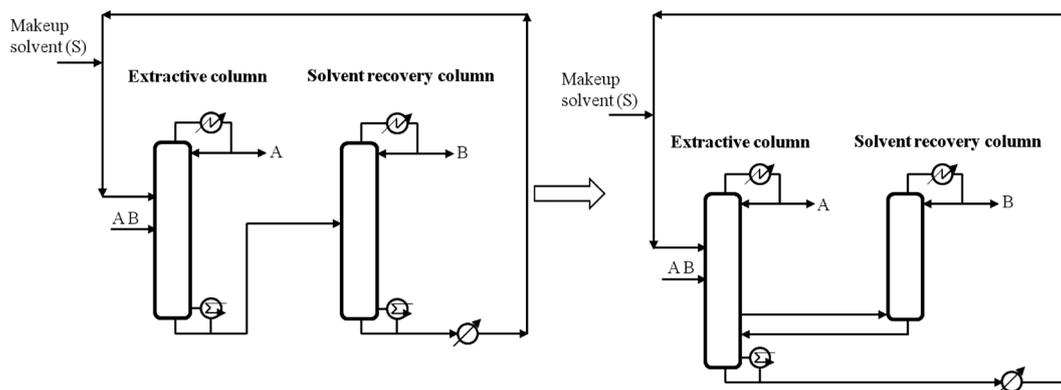


Fig. 12 Schematic diagram of extractive distillation and the proposed TCEDS-SS

decrease in the energy requirement was obtained in this design. Luyben (2008c) examined the case where the two columns are fully heat integrated and no auxiliary reboiler is used (Figure 10). The only energy input is the heat-transfer duty in the high-pressure column. Recently, Matsuda *et al.* (2011b) suggested a general procedure for internal integration of pressure-swing distillation and illustrated the separation of a binary acetonitrile-water mixture, which forms pressure-sensitive minimum-boiling azeotropes.

1.3.2 Azeotropic distillation The term azeotropic distillation applies to a class of distillation techniques characterized by fractional separation based on the azeotropic properties of the system. The agent responsible for the specific azeotropic behavior, which is known as an entrainer, can either be present in the feed mixture (self-entraining process) or can be added to the process to separate the mass (Widagdo and Seider, 1996; Doherty and Malone, 2001; Guedes *et al.*, 2007; Gutiérrez-Guerra *et al.*, 2009; Ibarra-Sánchez and Segovia-Hernández, 2010). To make the separation feasible, two important characteristics of this additional azeotrope are important. First, the azeotropic temperature of one additional azeotrope should be the minimum temperature of the whole ternary system. Second, this azeotrope should be heterogeneous so that natural liquid-liquid separation can be performed without any energy requirements in a decanter at the top of the column (Luyben and Chien, 2011). The separation of an azeotropic mixture A-B can be accomplished using a two-column sequence (shown in Figure 11). A detailed description of this process can be found in the book by Luyben (Luyben and Chien, 2011). The two columns can be integrated into thermally coupled azeotropic

distillation sequences (TCADS-SS), as shown in Figure 11. Up to now, there have been few papers reporting on retrofitted TCADS-SS. One study on an equivalent azeotropic DWC for the grass-roots case (Midori *et al.*, 2001) was reported to have good potential for energy savings.

1.3.3 Extractive distillation Extractive distillation uses a solvent that is generally nonvolatile, has a high boiling point, and is miscible with the mixture. This solvent interacts differently with the different components of the mixture, thereby causing changes in their relative volatilities (Bravo-Bravo *et al.*, 2010). This produces new three-part mixtures to be separated by normal distillation. Moreover, the process makes it possible to obtain a pure compound at the top of the column, with the other components, together with the solvent, collected at the bottom. The solvent can be separated easily in a secondary distillation or solvent recovery column because of the high boiling point of the solvent.

Extractive distillation (Figure 12) is used widely in many processes (Arifin and Chien, 2008; Gil *et al.*, 2008; Hernández, 2008; Gil *et al.*, 2009; Gutiérrez-Guerra *et al.*, 2009), but its high energy consumption is a major disadvantage that should be overcome. To reduce the energy requirements, TCDS can be utilized through the implementation of interconnecting streams to achieve thermally coupled extractive distillation sequences (TCEDS-SR) (Gutiérrez-Guerra *et al.*, 2009; Ibarra-Sánchez and Segovia-Hernández, 2010).

1.4 Side stream column

A side distillation column can be used to separate any non-azeotropic multicomponent mixture into three products (Glinos and Malone, 1985). Therefore, it can often

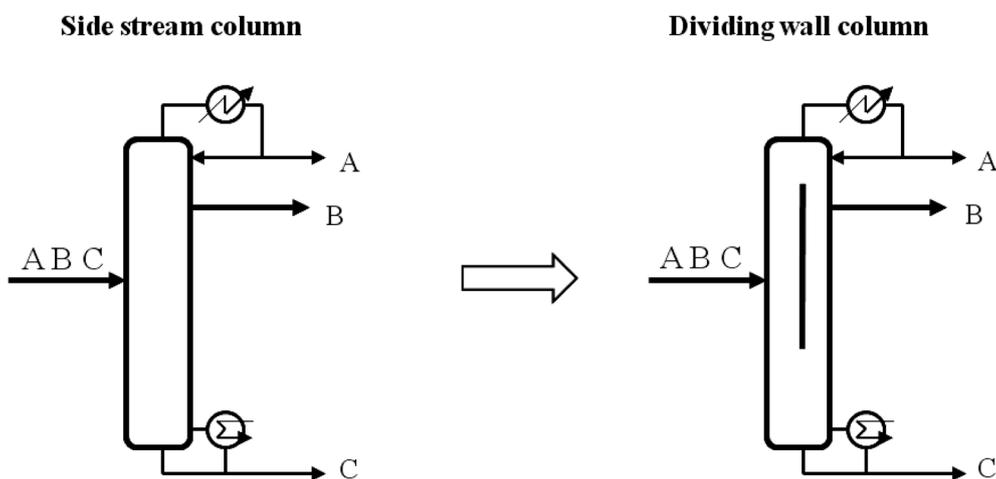


Fig. 13 Schematic diagram of side-stream distillation and the retrofitted DWC

replace a sequence of two columns. On the other hand, the purity of the side distillation product is restricted by thermodynamics and by the nature of the distillation process. These columns are normally appropriate either as prefractionators (the side stream is fed to another column for further separation) or to generate recycle streams when there are no strict requirements on the recycle composition. They are also used widely in the petroleum industry, where blends are produced rather than pure products.

Asprion and Kaibel (2010) compared a conventional side stream column and a DWC for the separation of *n*-hexane, *n*-heptane, and *n*-octane. The column has 50 theoretical trays. In the conventional side-stream column, a *n*-heptane concentration of 82% can be reached with a considerable amount of entropy of mixing generated on the feed plate. In a DWC, the generation of the entropy of mixing on the feed plate is avoided, and an *n*-heptane concentration of 98% in the side product can be reached with the same heat input. Therefore, a retrofit replacing a side distillation column with a DWC (Figure 13) can result in significant energy savings (Ennenbach *et al.*, 2000; Kolbe and Wenzel, 2004; Slade *et al.*, 2006).

2. Reported and Patented Applications of TCDSs and DWCs

2.1 Retrofits

A prefractionator arrangement and Petlyuk column proposed for a NGL retrofit were found to be beneficial not only in terms of achieving energy savings or capacity improvement but also in their ability to exploit the existing hardware to the maximum (Amminudin and Smith, 2001). Of the two options, the prefractionator arrangement provides a better option than the Petlyuk column, because the former arrangement is much simpler to design with the complete use of existing equipment. Furthermore, the prefractionator arrangement, which allows the heat load to be distributed between the reboilers, offers much greater added capacity to the separation train. The external

flows from the reboiler and condenser of the prefractionator are easy to control. The energy savings generated from this arrangement are 27% compared to the performance of the existing column arrangement. Another significant energy benefit will be the distribution of the hot utility consumption between the two reboilers, which will reduce the use of high-temperature utilities in the reboiler for the deisobutanizer (main column).

The use of the DWC for retrofitting was also examined (Triantafyllou, 1991; Amminudin and Smith, 2001). Triantafyllou reported that the DWC could not be used for capital savings but was useful for energy savings or process debottlenecking through the more efficient use of existing columns. He suggested several arrangements involving the use of DWCs in two existing conventional columns. He first proposed two DWCs in parallel, as shown in Figure 9. In this arrangement, the feed can be divided into two smaller feeds, and the dividing walls are placed inside the two columns. Each of the two columns could then have three products and could perform similar separations. The major drawback of this split arrangement is that in each DWC, only a fraction of the total number of stages are used effectively to achieve the same separation as before. To accommodate such restrictions, the columns must be operated at a much higher reflux ratio, which could jeopardize the energy savings. In the case of process debottlenecking, where energy savings might not be the top priority, the higher reflux ratio needed to meet the intended product specification results in a much higher volumetric flow rate in the column. Because of the fixed column diameter, however, the column may not be able to handle such an increase in volumetric flow rate. To fully exploit the columns and overcome potential problems with the split arrangement, he suggested two DWCs linked together, as illustrated in Figure 9. This essentially maintains a single DWC but splits it into two column shells. The column can now be operated at a much lower reflux ratio and utilizes all the column trays to achieve the desired separation.

Interestingly, Long and Lee reported the design and op-

timization for a retrofit in which an extractive distillation sequence was converted to a thermally coupled extractive distillation sequence using a side rectifier (Long and Lee, 2013b). This process could be adapted easily to include the hydraulic capacity and the total number of stages of the existing columns involved in the retrofit. Retrofitting of an extractive distillation sequence can achieve significant energy savings with few modifications. Furthermore, retrofitting to a TCEDS-SR can not only utilize existing columns, but can also increase the process capacity. In several cases, however, this can create a bottleneck in the column. Long and Lee (2013d) utilized fractional utilization of area (FUA) to identify bottlenecks in a retrofitted TCDS systematically and proposed a novel strategy for the use of a side reboiler or a side condenser for debottlenecking the column. The use of a side reboiler or a side condenser in a retrofitted TCDS could debottleneck the column and increase the process capacity. This can reduce the temperature difference between the top and side reboiler location, or between the bottom and side condenser location, which allows potential use of a heat pump by utilizing the heat from the top vapor stream or side vapor stream, respectively. The column grand composite curve (CGCC) was used to indicate the thermodynamic feasibility of the implementation of the heat pump system into the TCDS.

ExxonMobil successfully refurbished a conventional tray xylenes distillation column (Slade *et al.*, 2006). This column takes a xylene side stream from the reformat to feed an aromatics plant to produce higher value products. The entire project cycle is detailed in this report, including the process design, hydraulic design, mechanical design, manufacture, testing, and site work. Changing the column configuration to a DWC resulted in energy savings of up to 53% along with improvements in the xylenes' purity. The column condenser and reboiler did not require any modifications. The product cooler was also reused without modification, even though it was rather oversized. The design required several new nozzles to be installed for the bypass, feed, and product draw-off, plus new instrumentation.

Kolbe and Wenzel (2004) presented some industrial examples of the implementation of a DWC by Uhde. One of them is the revamp of a side distillation column for processing pyrolysis gasoline at Ruhr Oel. The project was driven mainly by the modified European specifications for gasoline, which limit the benzene content in mixed gasoline (overhead product plus bottom product) to a maximum of 1% by volume. By removing the middle section of the column shell equipped with the trays and inserting a divided-wall segment equipped with structured packing, this project increased the benzene yield and concentration in the side-draw and the column capacity. Interestingly, the modification was planned in such a way to allow the complete reconstruction from the "ready for opening" to the "ready for feed-in" stage in a plant shutdown period of only 10 d. In this narrow time period, the existing column shell was cut into three pieces. A part of the adjacent piping was also demolished. The prefabricated new column section was then

partly wedged with the new piping attached. The internals for the new section were installed and leveled on-site. Some of the pump sets were also replaced to match the new debottlenecking capacity.

A DWC developed by our team (PSDC) along with the LG CRD team was implemented successfully and started up in the LG Naju plant in 2008. This commercial DWC was designed by the DWC project team only with domestic technology. Start-up of the commercial DWC was completed successfully. Changing the column configuration to a DWC resulted in improved product purity and significant energy savings (up to 40%). This DWC is considered the first commercial DWC in Korea.

Six applications of industrial importance were selected, and conventional two-column systems were designed, which were assumed to be currently in operation in the plants (Premkumar and Rangaiah, 2009). The retrofitting of these systems to implement DWCs was then studied. The results showed that retrofitting the existing two-column systems with DWCs is quite attractive, both economically and for the reduced energy requirements.

Recently, Long and Lee (2013e) reported the potential for retrofitting a side distillation column as a DWC. The minimum energy requirement for the separation of a multicomponent mixture was used in this feasibility study, whereas the response surface methodology was used to minimize the reboiler duty. These results showed that the DWC can save up to 25.16% in energy. Furthermore, the maximum flooding was reduced from 87% to 80%, which has the potential to increase the plant production capacity.

2.2 Debottlenecking

For an existing distillation process with a fixed feed composition, there will be a maximum feed flow rate for the separation below which certain fixed product specifications can be met (Liu and Jobson, 2004a). The bottleneck of the process is that a particular piece of the installed equipment cannot accommodate flow rates higher than those associated with this maximum feed flow rate. Above the maximum feed flow rate, the column producing the main product might no longer be able to perform as required, or the downcomers in the column may flood, etc. The goal of such a retrofit design is to identify and remove such bottlenecks.

DWC can be used to remove the bottleneck phenomenon as well as improve the energy efficiency when increasing the throughput. One of main ideas is to shift the increased load to the subsequent columns and have the DWC take care of the load (Long *et al.*, 2010). A range of possible distillation arrangements were studied, along with the DWC configuration. The results suggest that the DWC can operate as an efficient replacement for a conventional column in a retrofit for the debottlenecking of distillation processes, while requiring less investment and energy costs than conventional distillation, Petlyuk column, and prefractionator arrangements.

The key to a successful retrofit lies in maximizing the utilization of the existing equipment while simultaneously

minimizing the new hardware to reduce the capital costs. Nevertheless, these modifications require plant downtime. In many retrofit projects, downtime is the largest economic factor, because it leads to a loss of production and an interruption of the product supply to customers (Amminudin and Smith, 2001). On the other hand, each retrofit should be considered based on the specific conditions of each particular case, such as the component characteristics, operating conditions, number of trays, equipment lifetime, construction material, and feed composition. Long and Lee (2011) proposed some rules for achieving a successful retrofit.

3. Discussion

3.1 Constraints

In general, a retrofit project for a distillation process covers a wide range of modifications and utilizes existing processes ranging from a simple modification or replacement of column internals only, to large modifications of the column configuration, partial enlargement of the shell diameter and height, and modification of auxiliary equipment. In any case, the key to a successful retrofit lies in exploiting the existing hardware by maximizing the use of existing equipment while, at the same time, minimizing the need for new hardware to minimize the capital cost. To minimize the modifications in a retrofit, the number of trays of all columns and their diameter should be fixed to the same number in conventional distillation columns.

To integrate two columns into a single DWC, the operating pressure of the retrofitted DWC is normally adjusted to that of the column with the high pressure in order to condense the top product with the same cooling utility. This causes an increase in temperature in the bottom of the column. Sometimes, it is important to change the steam pressure level, such as from low-pressure steam to medium-pressure steam or from medium-pressure steam to high-pressure steam, which causes an increase in the operating cost. This can be a significant problem for some chemical plants whose products are sensitive to temperature. Polymerization and other reactions can occur when the column temperature increases, which causes fouling problems or produces unwanted products. In this case, the operating pressure of the DWC needs to be reduced to provide a lower operating temperature.

The top section of the two columns should also be considered, because many companies try to utilize the heat from the top vapor stream to produce steam. If this occurs, the attempt to reduce the energy requirement at the bottom will be unsuccessful. Note that the price of high-pressure steam is almost 1.1 times higher than that of medium-pressure steam, whose cost is also 1.1 times higher than that of low-pressure steam.

In principle, DWCs can be used as both tray and packed columns (Yildirim *et al.*, 2011). On the other hand, up to now, the majority have been constructed by Montz (2013) and used as packed columns by BASF SE. In some sequences that encounter fouling problems, the tray type is preferred,

whereas vacuum applications are dominated by structured packing. The integration of two columns, where one column has a fouling problem and another has structured packing, into DWCs can be a difficult problem. A packing type that is unsuitable for fouling problems should not be used, and the tray type, which has high pressure drop, will also be unsatisfactory when the column is operated at vacuum pressure.

Another problem is related to corrosion phenomena. In the production of a chemical plant, the construction material needs to be considered carefully because of corrosion. In the separation sequence, some columns have good corrosion resistance, whereas others do not. The addition of a new column, such as a post-fractionator or prefractionator, can also provide a process debottlenecking option (Liebman, 1991). Accordingly, the construction material for the new column, which is related directly to the investment cost and corrosion phenomenon, must also be considered. While some modification methods have been proposed to reduce the investment and operating costs, it is necessary to consider each particular case based on realistic conditions.

In the case of a retrofit to implement a side rectifier, a vapor stream is needed to thermally couple the two columns. Gas is normally transported when a compressor applies a pressure difference between the inlet and outlet, which results in more investment and operating cost. The pressure at the vapor stream tray location is normally designed to be higher than that in the bottom section of the side rectifier. Therefore, a compressor is not needed in this retrofit design. In some special cases, such as when it is necessary to prevent a reaction or product decomposition, the main column must be operated at a lower pressure than that in the bottom section of the side rectifier, which would require a compressor. Engineers should be aware of the additional investment and operating cost to determine if the project will continue.

A heat pump can also be used in a retrofit design, because they are easy to introduce and the plant operation is normally simpler than when heat integration is used. On the other hand, the high capital expenditure required for compressors make them industrially viable only for high-capacity, end-of-train (practically binary) separations of substances with similar boiling points, which require minimal compressor/compression costs. This is the case mainly in the separation of light hydrocarbons such as the C_2 , C_3 , and C_4 components, where the adiabatic exponents of the substances are large enough to enable significant temperature increases with relatively low compression effort (Stichlmair, 1988; Dejanović *et al.*, 2010; Matsuda *et al.*, 2011a). Furthermore, in a heat pump, usually only the heat recovery duty of the reboiler in the distillation column is considered, while the heat introduced during preheating is not, or is at least less recognized (Matsuda *et al.*, 2011a). When a heat pump is used, engineers should consider the reactions that can take place as the vapor pressure and temperature are increased. In some cases where this is a problem, a heat pump cannot be used even if the energy requirements can be reduced.

3.2 Technical

When two columns are retrofit to form a DWC, the selected, existing column is modified by the addition of a middle section that houses the dividing wall (Premkumar and Rangaiah, 2009). This column will be cut on-site into two portions to form the top and bottom sections of the retrofitted DWC. The middle section of the retrofitted DWC is shop-fabricated and would be available before the actual on-site retrofitting begins. This section is first welded to the top of the bottom section, and the removed top portion will then be welded on top of the middle section to complete the column. In this exercise, the number of stages in the existing column would be sufficient to meet the required number of stages in the top and bottom sections of the DWC. Essentially, the existing column is fully utilized, limiting the column modification to the addition of a middle section only. In contrast, the retrofit of a side column to implement a DWC includes removing the existing trays and adding new trays (if necessary) and a new dividing wall into the middle section. Another approach is to cut the existing column shell into three pieces (Kolbe and Wenzel, 2004), where the prefabricated new column section is then welded in. The internals for the new section are installed and leveled on-site. In addition, some of the pump sets are replaced to match the new debottlenecking capacity. The design, engineering, and operation of the DWCs was found to be practicable without difficulties. From a technique point of view, the retrofit of a side stream column to implement a DWC can be preferable over retrofitting two columns to form a DWC.

These modifications incur significant plant downtime (Long and Lee, 2013b). In many retrofit projects, downtime is the largest economic factor, and a significant amount can lead to a loss of production and an interruption in product supply. In an integrated facility, where plants depend on each other, such downtime can disrupt other downstream processes. In project discussed in the paper by Long and Lee (2013b), the feed and aniline stream nozzles were moved from the 21st and 28th trays to the 20th and 29th trays, respectively, which required some modifications. Energy savings of up to 31.65% are still possible when the feed locations remain in the conventional positions. Even though the optimum point provides better operating cost savings, keeping the same location of the feeds is preferred because fewer modifications are required. The operating cost and investment are a trade-off to be considered in a retrofit design (Long *et al.*, 2010).

3.3 Economic analysis

Estimating the capital cost of a retrofit project is much more difficult than a similar estimation for a new design (Smith, 2005). The installation factors for equipment in a retrofit can be completely different from those in a grass-roots design and can be higher or lower. Retrofit installation factors, shown in **Table 1**, will most often tend to be higher than those in the grass-roots design and can be much higher. This is because existing equipment might need to be modified or moved to allow the installation of new equip-

Table 1 Modification factors (Smith, 2005)

Column modification	Modification factors
Removal of trays to install new trays	0.1 for the same tray spacing
	0.2 for the different tray spacing
Removal of trays to install packing	0.1
Removal of packing to install new trays	0.07
Installation of new trays	1.0–1.4 for the same tray spacing
	1.2–1.5 for different tray spacing
	1.3–1.6 when replacing packing
Installation of new structured packing	0.5–0.8

ment.

3.4 Controllability and operability

3.4.1 Controllability The integration of columns leads to changes in the operating mode and controllability of such an integrated system (Serra *et al.*, 2000; Serra *et al.*, 2003; Segovia-Hernández *et al.*, 2007; Wang and Wong, 2007; Kiss and Bildea, 2011). Therefore, all the benefits of a TCDS and DWC are possible only when a good control strategy is available and can achieve the separation objectives (van Diggelen *et al.*, 2010). Substantial work has been done in this area. The overall results have shown that not only is it possible to control thermally coupled distillation well, but such distillation can sometimes exhibit dynamic responses that are easier to manage than those occurring when a conventional distillation column is used. In particular, Segovia-Hernández *et al.* (2004) reported the results of a comparative analysis of the feedback control responses to set-point changes of three thermally coupled distillation schemes and two conventional distillation sequences for the separation of ternary mixtures. To compare the dynamic behavior, the responses to set-point changes under closed-loop operation with proportional-integral (PI) controllers were obtained. For each separation scheme, the parameters of the PI controllers of the three composition control loops were optimized using the integral of the absolute error criterion. The effects of the feed composition and of the ease-of-separability index were considered. The dynamic tests showed that in many cases, the TCDS outperformed the conventional distillation sequences in terms of its dynamic responses. The results suggest that there are cases in which the energy savings provided by the TCDS systems do not conflict with their dynamic properties. Similarly, the controllability of the TCDS for the separation of ternary mixtures was also compared with those of the conventional direct and indirect sequences (Segovia-Hernández *et al.*, 2002). The closed-loop responses to set-point changes were evaluated, and the controllers were tuned to minimize their integral of the square error (ISE) values. The results suggest that the integrated systems exhibit better control properties than the sequences based on conventional distillation columns. This provides a further incentive for the use of such

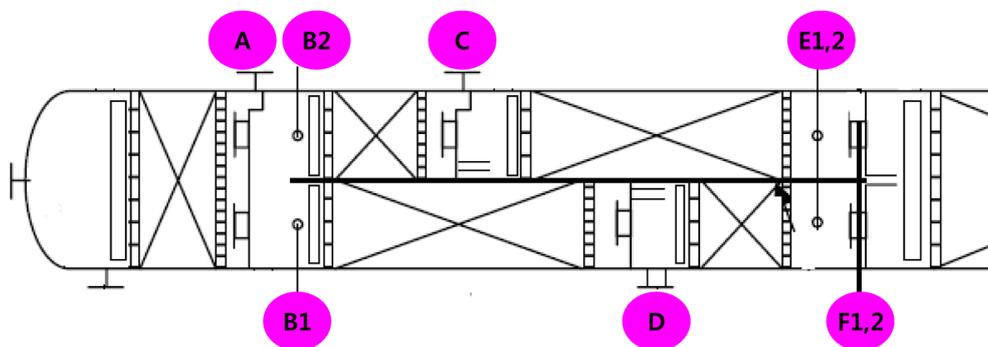


Fig. 14 DWC capable of two operation modes (Shin *et al.*, 2011)

integrated systems.

One study reported the production of ethyl acetate from ethanol and acetic acid using three reactive thermally coupled systems (Barroso-Muñoz *et al.*, 2007). Dynamic closed-loop responses were obtained for the most energy-efficient reactive distillation scheme (Petlyuk column). The results showed that with this complex scheme, one can achieve changes in the set point and also eliminate the effect of disturbances using only simple PI controllers tuned using Ziegler and Nichols's method. From these results, they concluded that TCDS has significant advantages over the classical process used to produce ethyl acetate.

Mutalib and Smith (1998) analyzed two control configurations (L-S-V and D-S-V) for the Petlyuk column and reported that both schemes achieve satisfactory control, with the D-S-V structure providing better dynamic performance. Furthermore, Mutalib *et al.* (1998) reported the results from both dynamic simulations and the experimental tests for the Petlyuk column. Through temperature control, they were able to obtain stable performance of the column under feed condition disturbances.

A profile position control scheme was proposed to overcome the control problems (Cho *et al.*, 2009). Relative gain array analysis and singular value decomposition were used to determine the optimal control configuration. A dynamic simulation showed that the profile position-product composition cascade control can maintain the product purity at the desired values despite feed disturbances and internal disturbances. Kiss and Rewagad (2011) compared several conventional control structures based on proportional-integral-derivative (PID) control loops enhanced using the liquid split as an additional manipulated variable, thereby implicitly achieving minimal energy requirements. They reported dynamic results showing good DWC controllability, relatively short settling times, and low overshoot.

Recently, two-point temperature control structures for DWCs were investigated to overcome the difficulties arising from their complicated natures (Kim *et al.*, 2012). The control performance for the DWCs was assessed under nine different feed conditions characterized by the composition of an intermediate component and the relative volatilities. Steady-state and dynamic simulations were performed to analyze the closed-loop responses for various two-point

temperature control structures for the DWCs. Proper control strategies depend strongly on the feed characteristics, particularly on the relative volatility of the feed components. The reported control structure evaluations are based on rigorous simulations, and basic guidelines for selecting proper control structures for the DWCs have been proposed in relation to the feed conditions. Kiss and Bildea (2011) published a more detailed review of the available control strategies for DWCs.

3.4.2 Operability A DWC with two operating modes (**Figure 14**) was developed to minimize the risks associated with its operation and to ensure the safe retrofitting of an existing column (Shin *et al.*, 2011). At the top of the divided wall section, the liquid coming down from the rectifying section can be split in a controlled manner between the two sides of the wall using a total liquid trap-out tray. Then, some of the total liquid is sent to the prefractionator side, and the remainder is sent to the side stream side (Kiss and Bildea, 2011). Therefore, an internal liquid split is available for control purposes.

At the bottom of the divided wall section, the vapor is split in proportion to the cross-sectional area of each side, depending on the hydrodynamic conditions (above all, the pressure drop and flow resistance). The cross-sectional area of each side is fixed by the physical location of the wall, which is already set at the design stage and cannot be changed later during operation. Thus, the vapor split is not adjustable during operation for control purposes because the location of the wall fixes how the vapor flow splits between the two sides of the column. Therefore, in most commercial DWCs, there should be a device that splits the liquid coming from the column overhead into the sections divided by the wall, i.e., a prefractionation section and main column section.

The splitting of a liquid stream can be achieved conceptually through the simple arrangement of a pump, valves, pipes, and a vessel, as shown in **Figure 15** (Shin *et al.*, 2013). Nevertheless, such splitting still requires an additional plot area, equipment, and instruments. Such an increase in the equipment inventory within the system should be minimized, so this concept is rarely used in practical applications of DWCs.

The first-generation reflux-splitting systems are moving-

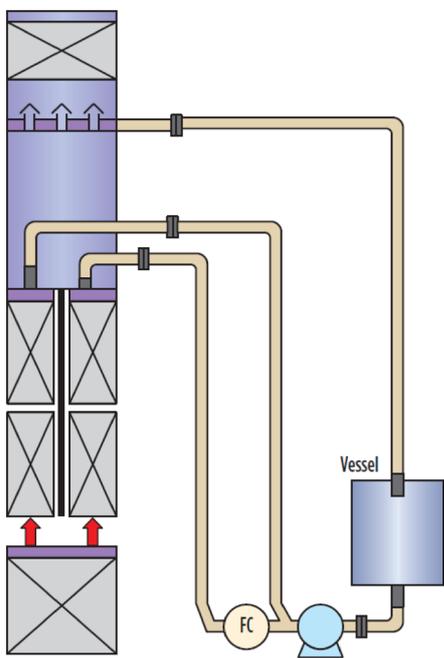


Fig. 15 Conceptual design of liquid splitting in a DWC

bucket reflux splitters (Shin *et al.*, 2013; Montz, 2013). These early systems consisted of a casing that was subdivided into three chambers. The feed chamber was located above where the liquid was directed onto either the prefractionation or main column chamber, depending on the position of the dividing body. The split ratio was controlled by adjusting the timing of the hollow inner bucket into the prefractionation or the main column chamber. On the other hand, the moving elements in the first-generation reflux splitter could be damaged by the constant movement of the mechanical parts (Shin *et al.*, 2013). In a petrochemical plant, the splitter should operate at least 8,400 h/y without mechanical problems. For example, the naphtha cracking center (NCC) has more severe requirements to address any possible equipment malfunction, because it needs to have run duration of at least 3–4 years without regular scheduled plant maintenance. A more reliable liquid-splitting device must be used in such cases. For this purpose, a manual-type reflux splitter that requires no moving element was devised and installed successfully on several commercial DWCs in LG Chem plant sites (Lee *et al.*, 2010). The internal structure of the manual reflux splitter appears complex, but the basic

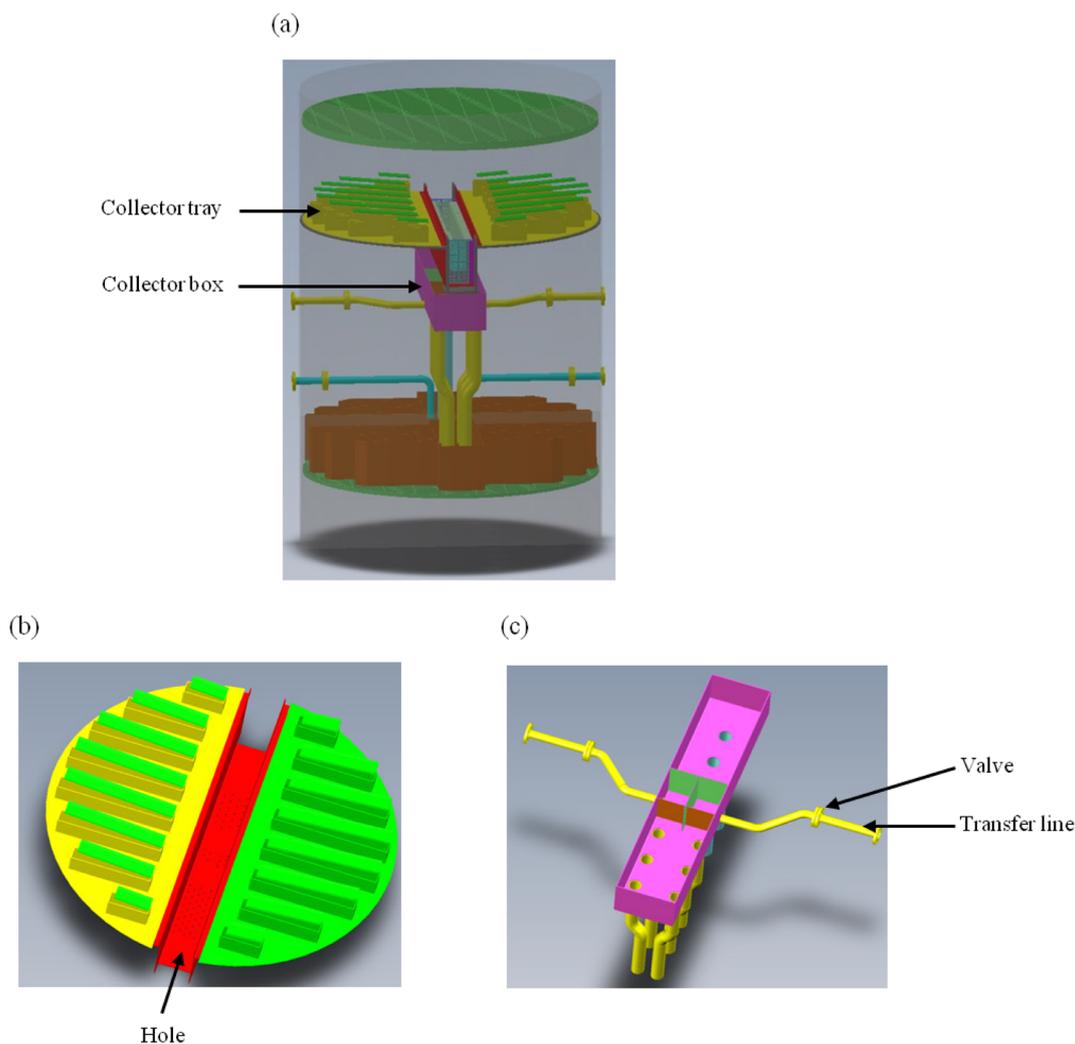


Fig. 16 In-the-column reflux splitter: (a) overall, (b) collector tray, and (c) collector box and transfer lines (Lee and Kim, 2012)

principle is quite simple. The splitter is divided into several sections that receive the liquid drawn off from the column overhead. An on/off type of automatic valve is mounted to each section. If the valve is closed, the liquid received will overflow into the main section, which is connected directly to the main column without a valve. By opening the different valves in a controlled way, the split ratio can be controlled to predetermined values. The control range of the split ratio can be determined from a sensitivity study of the DWC column for possible operation scenarios, such as variations in the feed compositions and product quality. The performance of the reflux splitter can be confirmed before it is mounted into the DWC column using a water-run test.

The latest development in the reflux-splitter system increases the unit reliability through simple modification of the conventional distributor and collector tray, as shown in **Figure 16** (Lee and Kim, 2012). The in-the-column reflux splitter consists of a modified collector tray, a collector box, and two transfer lines. The collector tray gathers the liquid from the top section and transfers it to the collector box located below. The holes in the middle of the collector tray (see Figure 16(b)) divide the liquid into four sections in the collector box with predefined fractions. As shown in Figure 16(c), the splitting ratio can be adjusted by the on/off operation of two valves located on the transfer lines (see Figures 16(a) and (c)) at the outside of the column. If the two valves are open, the liquid stream from the middle sections goes to the pre-section via the liquid transfer lines, which are connected to the distributor for the prefractionator section. Therefore, this state will increase the liquid flow to the prefractionator section. If the two valves are closed, the liquid flow to the main section will be increased by the liquid overflow to the main section. Four combinations in the on/off valve are possible, so four split ratios are available. In the design phase, the required split ratios can be predefined considering the possible operational scenarios. The developed reflux splitter satisfies all the technical requirements or specifications described earlier and can reduce the fabrication and installation costs. This splitter type is simpler and cheaper than the manual reflux splitter and bucket splitters. In addition, it can reduce the column height, thereby providing an opportunity to install more trays or packing sections with a longer length.

According to Slade *et al.* (2006), achieving a liquid split in which all of the liquid is drawn off and pumped back while controlling the flow to either side of the wall requires a quite complicated and expensive system. To avoid this expense, a novel hybrid was developed using a chimney tray to regulate the bulk of the liquid in a fixed proportion and a gravity-fed external bypass to control the liquid split when required. This novel arrangement was tested in a full-scale test rig at Koch-Glitsch's Kirkby Stephen works.

In the side stripper, the splitting of a liquid stream can be achieved conceptually using the simple arrangement of a pump, valves, pipes, and a vessel, whereas friction can be used in the vapor stream in the side rectifier to control the vapor flow. On the other hand, suction side control is

needed for the vacuum side rectifier, which is applied on the top of the side column.

Conclusions

With global industrial growth, the applications of distillation are increasing in both variety and scale. Improving the energy efficiency of distillation processes and the related reduction of CO₂ emissions are becoming a part of global efforts toward more sustainability in processing industries. Process integration and process intensification in distillation are becoming dominant trends in the chemical processing industries.

1. The application of TCDSs and DWCs in retrofits of azeotropic and extractive distillation plants shows a remarkable reduction in terms of operating cost, but more study will be needed in this area.
2. In a retrofit project, both cost savings and operability need to be considered. Alternative distillation schemes to the use of a Petlyuk column, which do not have the classical problem of controlling the vapor transfer from one column to another, can be used in a retrofit.
3. Incorporating a heat pump or self-heat recuperation technology into retrofitted thermally coupled distillation columns, which achieves both internal and external heat integration, is a very attractive option for improving energy savings.
4. The operating conditions, construction material, lifetime, component characteristics, separation feasibility, number of trays, and effect of the feed composition on the DWC performance need to be considered to determine the best options. The results show that the DWC has apparent benefits in terms of investment costs, energy consumption, and space savings when used to remove the bottleneck problem.
5. Although controlling integrated systems such as TCDSs and DWCs is more difficult than controlling simple conventional columns, industrial experience suggests that it can be done satisfactorily.
6. The heat pump, TCDS, and DWC technology have some limitations. Thorough analysis of the constraints, technical considerations, economy, controllability, and operability in a retrofit using process integration and a thermally coupled sequence will give a more detailed and realistic overview. Of course, these techniques can not always be accomplished smoothly.
7. Process integration with a TCDS, particularly using a DWC, is an important breakthrough in both grass-roots and retrofit designs. DWC technology is expected to reduce the energy consumption at many refineries and chemical plants. DWC technology is now well established, and its applications are expanding rapidly as a standard option in many distillation processes.

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