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Heat integrated distillation operation

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ABSTRACT

Increasing energy demand, consequently high crude oil prices and growing concern for pollution motivated the researchers to explore more energy-efficient and environment-friendly process technologies. Although the heat integrated distillation has been researched for a number of decades, unfortunately it has not yet been commercialized mainly due to high investment cost, complex equipment design, control problem in consequence of severe interaction and nonlinearity, and lack of experimental data at sufficiently large scale to verify the theoretical predictions. It is true that some progress has been made in theory but for practical applications many questions still remain. Among the broader research needs the following areas are identified for heat integrated distillation column: rigorous dynamic modeling, optimal design, multiple steady state analysis, system identification, synthesis and implementation of high-quality nonlinear control, and importantly experimental evaluation. It is also suggested to investigate the feasibility of heat integration in the reactive distillation schemes and in the two distillation columns having no direct connections.

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1. Introduction

Distillation, which is the workhorse of chemical process industries, is quite energy intensive and accounts for an estimated 3% of the world energy consumption [1,2]. It is a fact that energy consumption in distillation and CO_2 gases produced in the atmosphere are strongly related. The higher the energy demands are, the larger the CO_2 emissions to the atmosphere are. This is because the energy is mostly generated through the combustion of fossil fuel.

To improve the energy efficiency, the heat integration concept was first introduced almost 70 years ago. The basic idea of heat integration approach is that the hot process streams are heat exchanged with cold process streams. In this manner, resources are used more economically. So far, various heat integrated distillation schemes have been proposed. An excellent review [3] has discussed recently these schemes. In the present review, many other heat integration schemes developed so far are discussed in depth. Although several heat integration techniques are covered in this paper, the main focus is placed on the so-called heat integrated distillation column (HIDiC) technique (Fig. 1).

At the end of 1930s, Brugma [4] first proposed a thermally coupled distillation column. This energy-efficient separation operation was re-introduced by Wright [5] and latter analyzed by Petlyuk [6]. Freshwater [7,8] is the first researcher who explored a novel distillation technique that describes the heat transfer from rectifying section to stripping section in a single unit. In the subsequent stage, Flower and Jackson [9] analyzed this approach performing different numerical experiments based on the second law of thermodynamics. Among the various energy-efficient distillation systems, the heat pump-assisted distillation column was first proposed in the mid-1970s [10–12]. The use of mechanical compression as heat pump is economical mainly in separating the low relative volatility mixtures. In recent years, the advanced forms of heat pump-assisted distillation technology are reported in literature [13,14].

The HIDiC concept was first introduced for gas separation processes by Haselden [15]. Since 1977, Mah and his team members [16,17] evaluated the heat integrated distillation column operation under the name of secondary reflux and vaporization (SRV), where only part of the rectifying and stripping sections was integrated for heat transfer. It is notable that they formulated a steady-state equi-

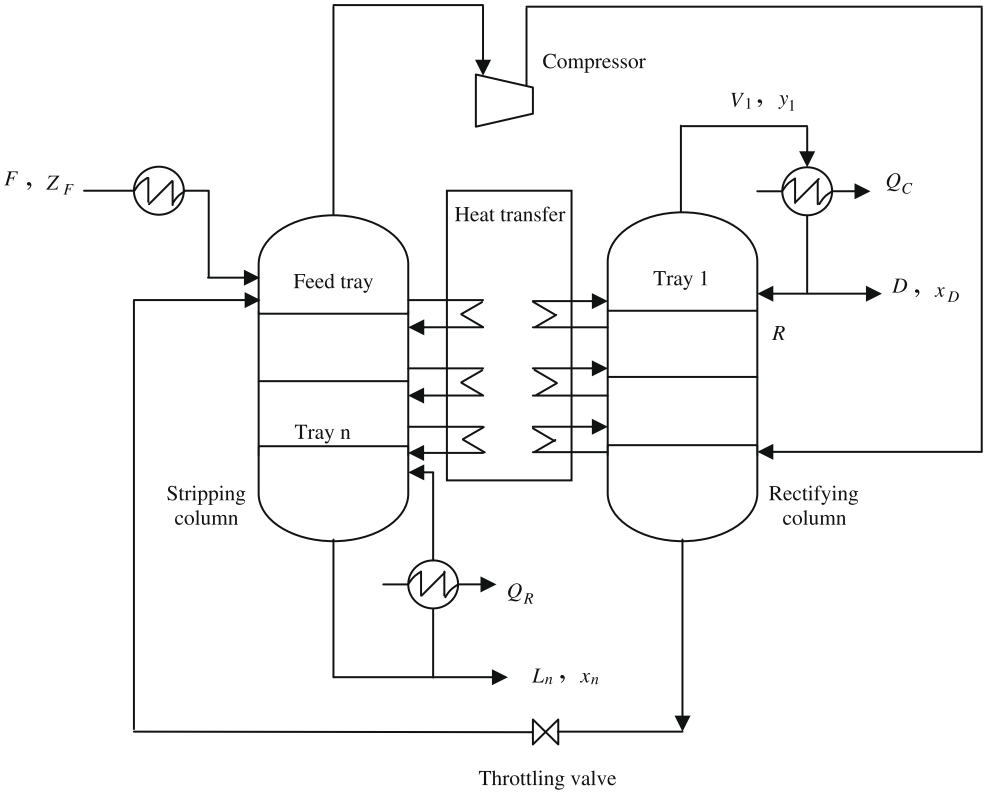

Fig. 1. A schematic representation of a general HIDiC scheme.

librium stage SRV model for the first time based on the Wang–Henke tridiagonal matrix method [18] incorporating the trim-reboiler, trim-condenser and compressor in the column structure. In the next, the authors [19,20] extended the internal heat integration to the whole rectifying and stripping sections.

Takamatsu, Nakaiwa and coworkers [21–24] are devoted from the mid 1980s for improving the heat integrated distillation technology. They thoroughly analyzed to evaluate the benefits offered by the heat integrated distillation column over a conventional distillation system. In the next, they [25–27] proposed a unique HIDiC structure that has neither a trim-reboiler nor a trim-condenser and this structure is usually referred to as the ideal heat integrated distillation column (i-HIDiC).

Recently, it is shown [28] that the i-HIDiC is more energy saving operation than the general HIDiC that includes both the reboiler and condenser along with the internal heat integration arrangement. However, when the feed rate has increased above the designated value, the ideal HIDiC is not economical. And in such a case, the HIDiC configuration is preferably used [3].

To achieve an appropriate heat balance, that is, to run the column without a reboiler and a condenser, the feed mixture needs to be preheated before introducing into the ideal heat integrated distillation column. This feed preheating arrangement can also be applied for the HIDiC, if required. When hot overhead vapor outlet of rectifying column of the i-HIDiC is reused as a potential hot utility for the feed preheating, the distillation configuration is referred to as the intensified i-HIDiC (int-i-HIDiC) [3,28]. It is worth noticing that the intensified i-HIDiC is more energy efficient compared to the i-HIDiC [28].

In the recent years, several groups are actively involved in research on energy-efficient distillation column design (e.g., [29–31]), analysis (e.g., [32,33]) and operations (e.g., [31,34]). Since 1990, several heat integrated distillation structures have also been patented [35–41]. However, a little progress has been noted on steady state multiplicity, optimal process design, system identification, nonlinear controller synthesis and implementation, and experimental testing. The main intention of this review is to focus the present status and future scope of research on heat integrated distillation columns.

In the present review, the work is organized as follows. At the beginning (Section 2), the importance of heat integration in distillation operation has been presented followed by the discussion on several energy-efficient separation techniques in Section 3. The next part (Sections 4 and 5) includes the recent applications of heat integration concept and then the different HIDiC structures. The scope of future research on HIDiC is highlighted in Section 6. Finally, in Section 7, the conclusions are presented.

2. Why heat integration in distillation operation?

Distillation is perhaps the most important and widely used separation operation that is used for about 95% of all fluid separation in the chemical industry and accounts for an estimated 3% of the world energy consumption [1,2]. In the US, about 10% of the industrial energy consumption accounts for distillation [42,43]. It is notable that more than 70% of the operation costs are caused by the energy expenses [44]. Surprisingly, the overall thermodynamic efficiency of a conventional distillation is around 5–20% [45,46].

In the distillation technique, heat is used as a separating agent. As illustrated in Fig. 2, it is conventionally supplied at the bottom reboiler to evaporate a liquid mixture and is lost when liquefying the overhead vapor at the reflux condenser. Actually, heat is added at the highest temperature (T_B) in the column, whereas that is removed at the lowest temperature (T_D). Interestingly, the thermal energy recovered at the condenser cannot be reused for heating other flows in the same distillation unit since the temperature of the coolant is usually sufficiently lower than that of the flows inside the column. Hence, it is said that in a traditional distillation column, heat is added at the reboiler and thrown away at the condenser. Actually, the energy is degraded over the temperature range of T_B–T_D and this is the prime reason of thermodynamic inefficiency of the conventional distillation technology.

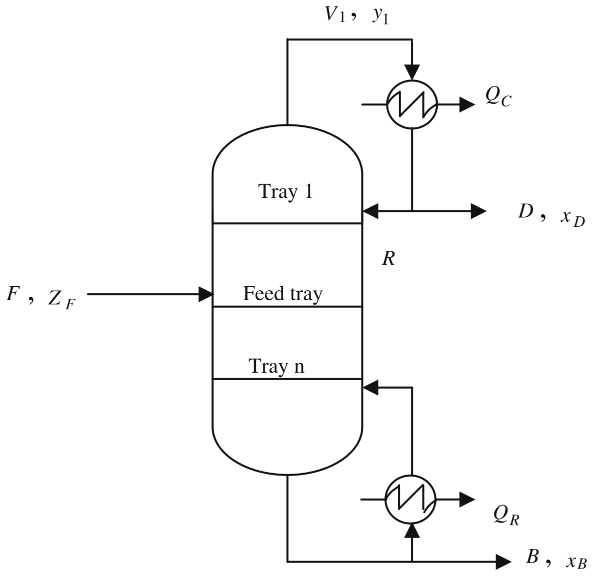

Fig. 2. A schematic representation of a conventional distillation column.

To improve the thermal efficiency of a distillation column, various methods, such as intercoolers–interheaters, heat pumps, secondary reflux and vaporization, and multiple-effect columns, have been explored. Basically, the idea is to reduce the external energy inputs by effectively utilizing the heat energy from the distillation units and to distribute the heat more uniformly along the length of the columns.

Few of the heat integration arrangements for distillation systems are exampled below. Many other arrangements will be discussed latter in a greater detail.

(i) For heat pump-assisted distillation columns, the overhead vapor is compressed and then used as a heating medium in the bottom reboiler.
(ii) For multi-effect columns, the hot distillate vapor stream may be thermally coupled with the next column bottom liquid stream in the reboiler.
(iii) For heat integrated distillation columns, the rectifying and stripping sections are internally coupled through heat exchangers. A compressor and a throttling valve are installed between the two sections for maintaining the driving force.

It is proven that the heat integration leads to a significant improvement in energy efficiency with reducing the reboiler and condenser duties. By proper process design, even sometimes, there is no need of any bottom reboiler and/or reflux condenser for a heat integrated distillation unit.

3. Several energy-efficient distillation techniques

To improve the energy efficiency of separation processes, several heat integrated techniques have been proposed so far. In this section, many of those important techniques are discussed with their relative strengths and weaknesses.

3.1. Pseudo-Petlyuk column

More than 70 years back, a thermally coupled distillation scheme was first patented by Brugma [4]. This energy-efficient process used for separating a ternary feed consists of a conventional side-stream tower and a prefractionator; both were equipped with condenser and reboiler. It is vertically divided by a wall through a set of trays to keep separated the feed stream from the side product. Wolff and Skogestad [47] have preferred to call this configuration as a pseudo-Petlyuk distillation column.

3.2. Divided-wall column

Wright [5] restructured the pseudo-Petlyuk column with eliminating the prefractionator unit. This configuration as shown in Fig. 3 is often referred to as divided-wall column (DWC) [48,49]. This is achieved when a vertical partition (wall) is introduced into a distillation column to arrange a prefractionator and a main column inside a single shell. The advantage offered by this partitioned column is that a ternary mixture can be distilled into pure product streams with only one distillation structure, one reboiler and one condenser. Obviously, this reduces the cost of separation. Moreover, reduced number of equipment units leads to a low initial investment cost.

Subsequently, Seader [50] designed a heat integrated separation scheme that includes a vertical column, in which a longitudinal divider separates the stripping section from the rectifying section maintaining a pressure difference between them. A plurality of heat pipes transecting the divider and extending between the stripping section and rectifying section are used for transferring heat energy by a working fluid from the rectifying section to the stripping section. The rectifying section is run at a higher temperature than the stripping section by compressing the overhead vapor of the stripping section prior to feeding into the rectifying section. In the next, Seader and Baer [51] performed experiment to obtain the heat transfer data for this heat integrated structure. The heat pipes were finned copper tubes and water was used as a fluid medium. In both the high-pressure and low-pressure columns, water was distilled. In this study, the effect of heat transfer on the mass transfer efficiency of the distillation tray was not taken into account. It is notable that this scheme allows flexible heat transfer area per tray.

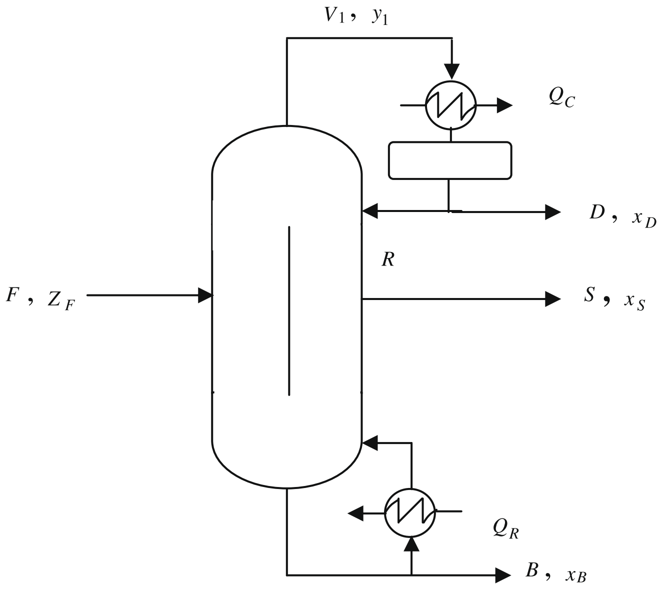

Fig. 3. A schematic representation of a Petlyuk distillation column (also known as divided-wall column).

To fractionate the feed mixtures containing four or more components, single tower distillation process with multiple vertical partitions was first proposed by Kaibel [48]. For multicomponent mixture separation, Agrawal [52] discussed various types of partitioned columns with their advantages and disadvantages. Due to the lack of experience in design and control, the dividing wall columns have not been used extensively in industry yet. However, their number is growing rapidly (40 units in 2004 worldwide) [53].

3.3. Petlyuk column

The divided-wall column proposed by Wright [5] was named as Petlyuk column after presenting a detailed theoretical study on this scheme by Petlyuk et al. [6]. With respect to the direct or indirect sequence, this reduced Petlyuk structure involves low initial investment and consumes less amount of energy reducing the operating cost. However, as compared to a conventional distillation unit, the Petlyuk column has many more degrees of freedom in both operation and design [47] causing difficulty in designing both the column as well as the control system.

As depicted in Fig. 4, the two-column Petlyuk scheme commonly consists of a prefractionator connected with a distillation shell that is equipped with only one reboiler and condenser. Many researchers (e.g. [49,54–58]) are involved from long before for the advancement of the Petlyuk column technology. The thermal coupling in a Petlyuk scheme has lead to large energy savings. But tight couplings between processing units result in difficulty in operation and control. Up to now, a little progress has been observed particularly on the operation and control of the Petlyuk distillation structure.

3.4. Multi-effect column

Multi-effect distillation approach used for separating multicomponent mixtures has received increasing research attention from the last decade (e.g. [59–62]). The basic idea of this method is to use the overhead vapor of the one column as the heat source in the reboiler of the next column. The columns may be heat integrated in the direction of the mass flow (forward integration) or in the opposite direction (backward integration). Fig. 5 displays a sample column representing a multi-effect scheme with a prefractionator for a ternary mixture separation. For the three-component feed, alternatively direct split or indirect split arrangement can also be employed.

These types of integrated arrangements have been proven to have substantial energy savings [2,63,64]. However, the potential drawback of the multi-effect system preventing the process from being commercialized is the operational difficulties owing to the nonlinear, multivariable and interactive nature of the process [61]. In the literature, there are few articles concerned with the optimal design, economics and controllability of these coupled arrangements.

3.5. Heat pump-assisted distillation column

In contrast to the multi-effect scheme, heat pump is primarily an approach for increasing the thermal economy of a single distillation column. The vapor recompression column (VRC) or heat pump-assisted distillation column had been implemented as an energy-efficient process in chemical and petroleum industries after the 1973 oil crisis. As shown in Fig. 6, the overhead vapor is pressurized by using a compressor to such a level that it can be condensed at a higher temperature supplying sufficient heat required in the reboiler.

The heat pump systems in distillation column have been well described in the past by Null [10], Finelt [65], Menzies and Johnson

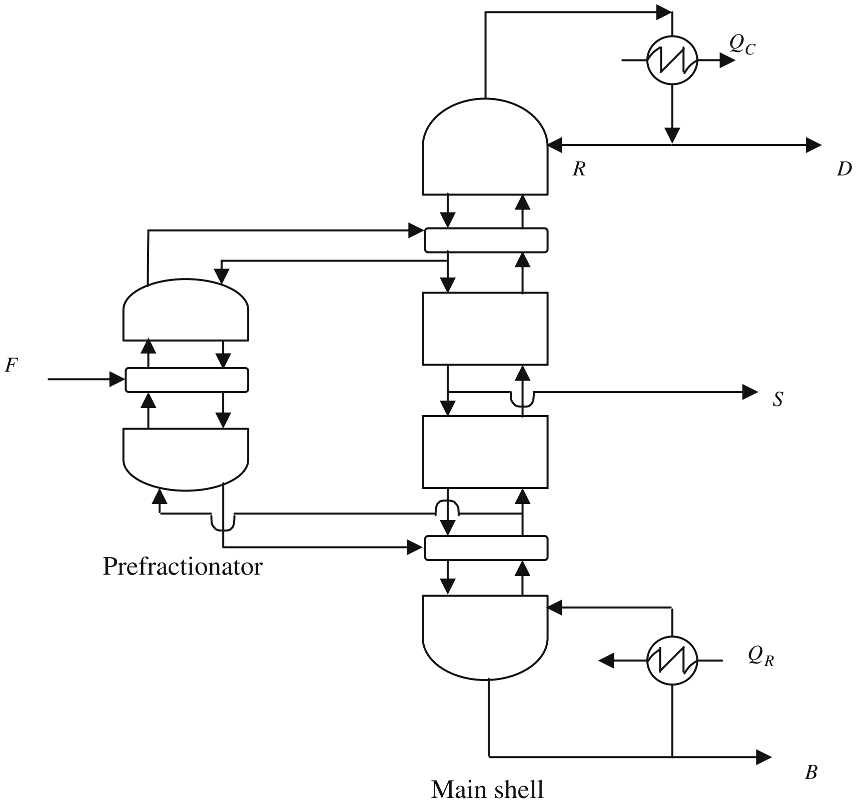

Fig. 4. A schematic representation of a two-column Petlyuk structure.

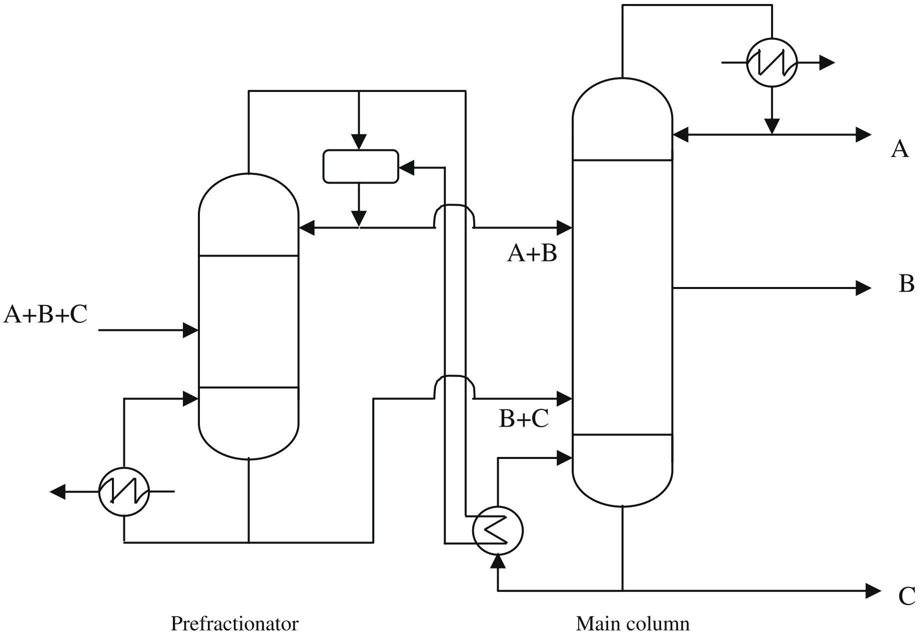

Fig. 5. A schematic representation of a multi-effect system for ternary (A–C) feed mixture.

[66], Meili [67], and other authors. There has been additional work in control using classical controllers and experimental equipments reported in literature (e.g. [68–73]).

The vapor recompression separation scheme has a potential of large energy savings for fractionating mainly the close-boiling mixtures, where owing to a small temperature difference between the top and bottom of the column, small compression ratios and consequently small compressor duties are required [74]. To fractionate the same close-boiling mixture using a conventional distillation column, high reflux ratios and consequently the large reboiler duties are required. Although, the heat pump-assisted column is advantageous with respect to energy savings mainly for separating the mixtures having relative volatility close to unity, it is capital intensive. To improve the heat pump based distillation technology, apart from the use of mechanical compression as heat pump, other advanced forms of heat pumps based on absorption, adsorption, etc. have been developed for distillation processes [13,14].

3.6. Diabatic distillation column

In the adiabatic distillation columns, heat is only supplied to the bottom reboiler and extracted from the reflux condenser. Hence, degradation of energy is a common phenomenon. As mentioned previously, this situation can be improved by spreading the heat requirements over the whole length of a distillation column. Such design consideration is referred to as diabatic distillation. As shown in Fig. 7, the heat transfer between the column and surroundings takes place on each tray of the column using a fluid medium through the coil. The idea goes back to the work of Fonyo [75,76].

In the diabatic distillation as described above, each tray needs an individual heat exchange circuit. Therefore, this structure has implementation problem because for each tray, two piercings in the shell are required. Moreover, the investment cost increases substantially. To alleviate the design problem, Rivero [77] and Le Goff et al. [78] simplified the diabatic column design with using two heat exchange networks; one is for rectifying section and another one for stripping section. This relatively simplified column involves a single heating fluid (usually steam) circulating from bottom tray to the next below the feed tray (stripping zone) and a single cooling fluid (usually water) circulating above the feed tray (rectifying zone). In addition to the extra investment, difficulty

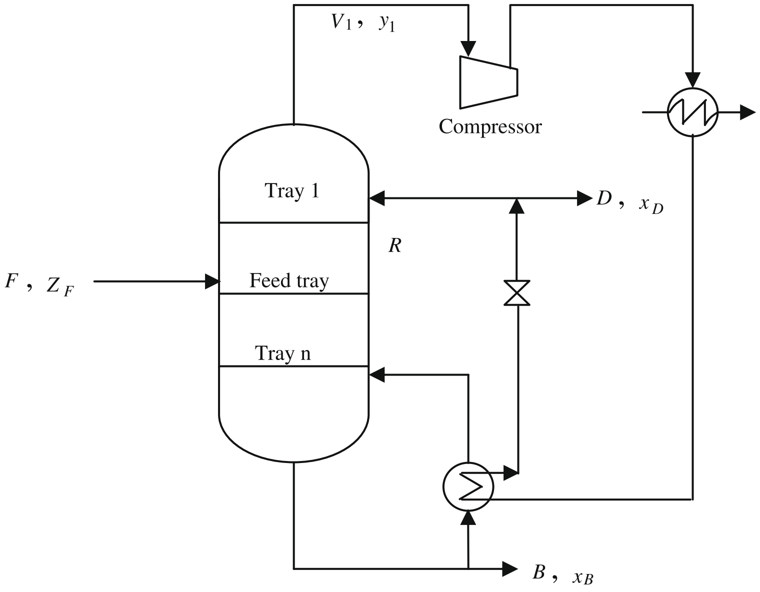

Fig. 6. A schematic representation of a heat pump-assisted distillation column.

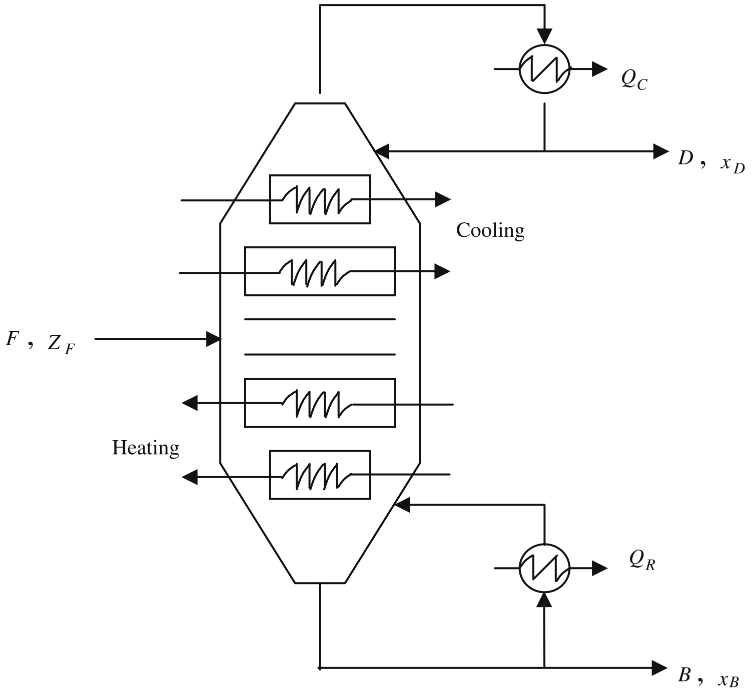

Fig. 7. A schematic representation of a diabatic distillation column.

arises in determining the optimal temperature and heating profiles ensuring operation at minimum entropy production. Many researchers (e.g. [79,80]) are working for minimization of entropy production rate in the diabatic distillation.

3.7. Heat integrated distillation column

By means of heat pump technology, separate rectifying column and stripping column can be heat integrated internally and this structure leads to a heat integrated distillation column (HIDiC) as shown in Fig. 1. At first, part of the rectifying and stripping sections was integrated under the name of SRV scheme [16] and latter the column design has been modified to the heat integration between whole rectifying and stripping sections [19]. A typical partial energy integrated distillation scheme is demonstrated in Fig. 8.

In the HIDiC scheme, the overhead vapor of the stripping column is compressed and then enters the bottom of the rectifying column. The rectifying column originally operates at a higher pressure. The liquid from the bottom of the rectifying column is introduced into the top of the stripping column, as is the column feed. The pressure of the recycled liquid stream from the rectifying column is equalized with that of the stripping column through a throttling valve. Here, the light product is the vapor leaving the top of the rectifying column (or the condensed liquid) and the heavy product is the bottom liquid of the stripping column.

In the HIDiC configuration, the stripping column operates at a relatively low pressure than the rectifying column. As mentioned, a compressor and a throttling valve are installed to adjust the pressures. The pressure differential implies a corresponding differential in operating temperature, which in turn enables energy to be transferred from the rectifying column to the stripping column through the heat exchangers. The heat exchange between the rectifying hot vapor and the stripping cold liquid leads to the reflux flow for the rectifying section and vapor flow for the stripping section. By this way, the reboiler heat load can be greatly reduced. The more heat that is exchanged, the less energy is consumed. By proper process design, even reflux-free and/or reboil-free operations can be performed.

The HIDiC operates at a lower compressor duty than its competitor vapor recompression column because the compressor of HIDiC runs only over the stripping section, whereas the vapor recompression requires the heat pump to operate over the complete temperature difference that exists in the system. It is shown [81] that the HIDiC can lead to energy savings of about 50% compared to a VRC scheme. However, this structure involves design complexity and large capital investment. Although the research is presently going on the dynamics and thermodynamic efficiency aspects, few design considerations have been reported so far in open literature.

3.8. Heat integrated batch distillation column

The energy integration concept has been further applied to develop the heat integrated batch distillation process [3,82,83]. As shown in Fig. 9, this is basically a concentric column, in which, the inner column serves as a rectifying section and the outer annular section acts as a reboiler. The annular column is partially filled with the feed mixture at the beginning. The vaporized feed is pressurized outside the column employing a compressor and introduced at the bottom of the rectifying section, which is maintained at higher temperature. The hot overhead vapor leaving the rectifying column releases heat to the annular liquid in the reboiler. Then, this is collected as distillate product. Moreover, the heat is transferred through the wall from the rectifying to stripping section causing liquid flow in the rectifying column.

Takamatsu et al. [83] performed a comparative study between the heat integrated batch distillation and the conventional batch distillation to show the superiority of the heat integrated scheme over its conventional counterpart with respect to energy efficiency.

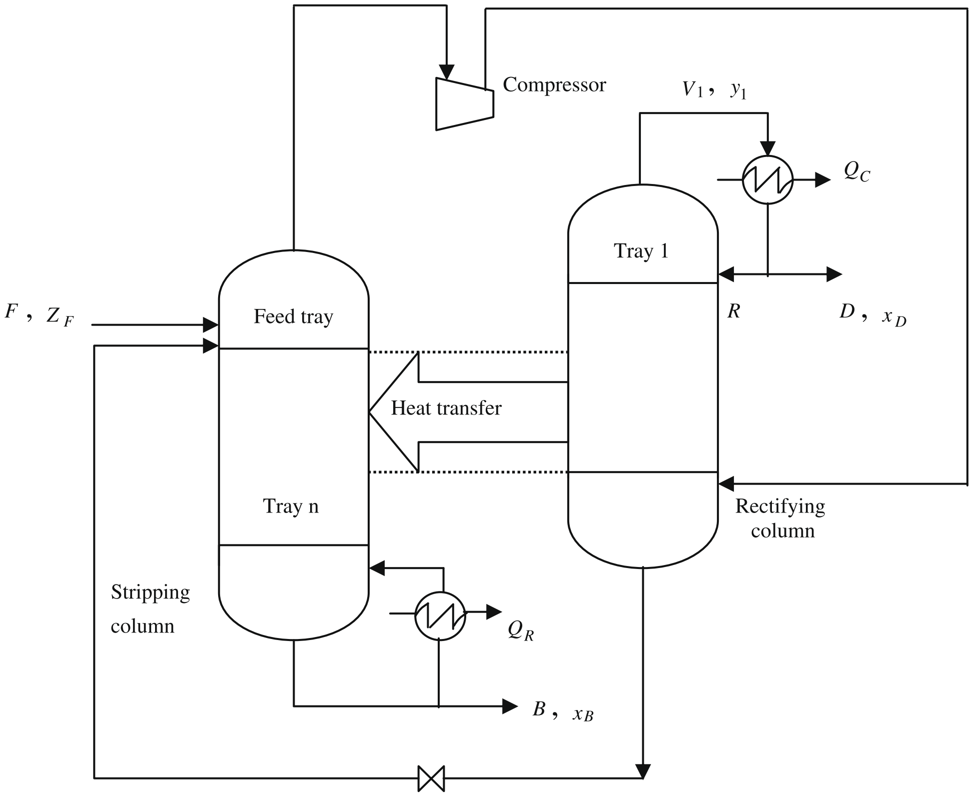

Fig. 8. A schematic representation of a partial HIDiC scheme.

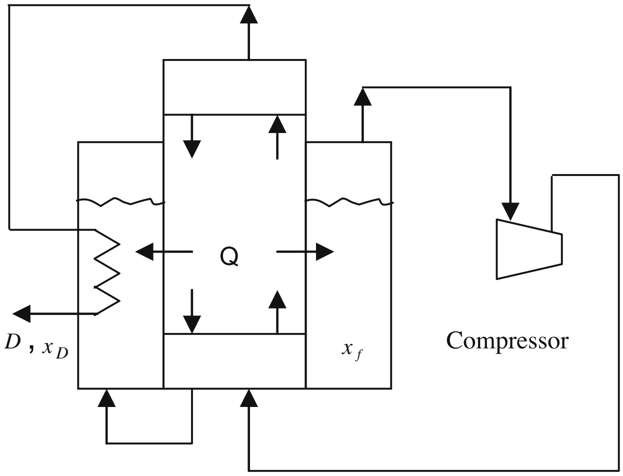

Fig. 9. A schematic representation of a batch HIDiC scheme.

At the start-up phase of the column, there must be some heat supplied from the external source. However, no more development has been noted on energy-efficient batch distillation.

3.9. Inter-coupled columns

Haselden [84] proposed a design approach for an inter-coupled energy-efficient scheme, which includes two parallel tray towers interconnected on every distillation tray by piping. The tubular heat transfer pipe is submerged in the tray liquid and therefore, the heat exchange area per tray is reduced. Moreover, this scheme requires large amount of piping between the adjacent columns leading to extra investment costs and heat losses to the environment.

Keeping the above issues in mind, subsequently Beggs [85] designed an improved version of the inter-coupled heat integrated structure, which has separate stripping and rectifying columns. A single heat exchange network is used to make tray-wise connection between two sections. But each tray is not necessarily connected in this approach. A heat transfer fluid medium is pumped through the network and that fluid receives heat along the length of the rectifying section and releases heat along the length of the stripping section. Special type of heat transfer trays with serpentine ducts inside the tray is used, which reveals that total heat transfer area is limited to the tray surface [74,86]. No more advancement is reported on this heat integrated arrangement.

3.10. Concentric heat integrated distillation column

Govind [87,88] and Glenchur and Govind [89] invented a concentric heat integrated column, in which, the annular stripping section is configured around the rectifying section. In this concentric column, the heat for an inner high pressure rectifying section is transferred by thermal conduction through a common wall or surface to an outer low pressure stripping column to enhance the energy efficiency. Moreover, by this way, the energy loss to the environment can be reduced because the heat in the rectifying section naturally tends to go to the stripping section. This scheme also provides greater efficiency because the annular stripping column is more effective than the typical cylindrical column. However, the heat exchange area is restricted to the column wall and there is limited flexibility for changing the heat transfer area per stage.

To alleviate the problem of limited heat transfer area, De Grauw et al. [90] patented a concentric column equipped with heat panels. The heat panels can be positioned in both the stripping as well as rectifying section. Heat panels arranged in the stripping section are in open connection with the rectifying section so that vapor from the rectifying section can enter the panels, condense inside and finally the condensed liquid can return to the rectifying section again. The heat released in this mechanism, in turn, evaporates the liquid present in the outer surface of the panels (stripping section). Similarly, when the heat panels are placed in the rectifying section, liquid from the stripping section can enter the panels via the open connection, evaporate inside and the vapor can flow back to the stripping section. As a consequence, some amount of vapor in the rectifying section condenses.

Recently, experimental heat transfer coefficients are evaluated and compared to model predictions for both heat panels positioned in the downcomer and that positioned on the active tray area between two trays [74]. A mass transfer model has also been experimentally validated and used to predict the tray efficiency. In addition to an appealing advantage of a large and flexible heat transfer area, this structure permits the designer to exclude certain trays with low or negative temperature driving forces from the process. It reveals that no heat panels are installed on these trays. For this scheme, the design complexity remains as a major cause of concern.

3.11. Fractionating heat exchanger

3.11.1. Shell and tube column

Aso et al. [91] modified the double pipe heat exchanger type column proposed by Govind [87] to the shell and tube column to improve the heat transfer. In this device, the low pressure low temperature stripping section (shell side) is configured around the tubes (rectifying section). By this way, a large and flexible heat transfer area is accommodated in the heat integrated separation process. But it is usually not suitable for trays [74] in both rectifying (small diameter tubes) and stripping sections (very complex tray design).

3.11.2. Compact heat exchanger column

The heat exchange surface area per unit volume of the compact heat exchanger, usually designed based on a structure of parallel flat plates, is significantly higher than that of the conventional shell-and-tube heat exchanger. This concept motivates the researchers to design the plate-fin type compact heat exchanger column. The idea of implementing plate-fin exchanger in the SRV structure was put forward in 1980 [92]. Subsequently, Tung et al. [93] conducted lab-scale experiments with a plate-fin design to validate their model. They used their model to predict the heat transfer rates and influence of internal heat transfer on the separation efficiency of the plate heat exchanger column. Actually, a plate-fin heat exchanger comprises of a number of parallel flat plates with intermediate corrugated plates (fins). The flat plates keep separated the process streams and provide primary heat exchange surface. In addition, the fins are used as secondary heat exchange surface. The plate heat exchanger is arranged in the heat integrated column for parallel vertical flows in alternating stripper and rectifier layers. In every layer there is a counter-current flow of gas and liquid, and the liquid flows downwards as a film on the walls.

In the next, Aitken [94] presented a heat integrated separation scheme that accompanies a plate heat exchanger filling the space between the vertical plates with corrugated sheets similar to structured packing. Recently, Hugill [95] and Hugill and van Dorst [96] showed that the plate heat exchanger column has a potential of energy savings of about 37% compared to a vapor recompression column. This separation structure offers a higher heat exchange area per unit volume of the equipment, a closer temperature approach, flexibility in design and modular structure. The major disadvantages [96] include: a need for complex distributors, plate-fin heat exchanger module size limitation (maximum height about 6–8 m, width about 2 m), flooding limitation with high liquid loads and surface wetting (turndown).

4. Recent applications of heat integration concept

4.1. Close-boiling mixture separation by i-HIDiC

Ideal HIDiC has already proved its superiority mainly in terms of energy savings over the other thermally coupled and conventional distillation columns. In order to broaden the application of ideal heat integration concept, recently the economical and operational feasibility of the i-HIDiC scheme have been explored for the separation of a close-boiling multicomponent mixture [31]. Actually, they have employed two ideal HIDiCs to separate a hypothetical close-boiling ternary mixture and considered two options of a direct and an indirect sequence just like its conventional counterpart.

Previously, Iwakabe et al. [97] computed 30% and 50% energy savings for the separation of two close-boiling mixtures, namely benzene/toluene/*p*-xylene and *n*-pentane/cyclopentane/2-methylpentane, respectively, using a HIDiC structure. Then Huang et al. [31] found that the ideal HIDiC system is much more thermodynamically efficient than a conventional distillation system. In their work, the process design has also been conducted in terms of the minimization of total annual cost (TAC). Finally, Huang et al. [31] analyzed the closed-loop controllability for the ternary mixture separation using the i-HIDiC and intensified i-HIDiC. Compared to the i-HIDiC, the intensified i-HIDiC showed worse closed-loop control performance with exhibiting large overshoot and longer settling time due to the positive feedback mechanism involved within the intensified structure.

4.2. Heat-integrated extractive distillation

A binary mixture having a low value of relative volatility (nearly unity) cannot be separated by ordinary distillation because the two components evaporate at nearly the same temperature at a similar rate. In this case, extractive distillation can be employed, in which a third component called solvent (high boiling and relatively non-volatile component) is added to alter the relative volatility of the original feed constituents.

Abushwireb et al. [98] investigated first time the operational feasibility of several energy-integrated extractive distillation technologies, such as Petlyuk column, divided-wall column and heat-integrated extractive distillation scheme. In the comparison between energy-integrated extractive distillation columns and conventional extractive distillation technique, the recovery of aromatics (benzene, toluene and xylenes) from pyrolysis gasoline using a solvent called *N*-methylpyrolidone has been considered in their work. The study includes the modeling, simulation and process design of the energy integrated configurations and the optimum design is performed by minimizing the total annual cost (objective function).

Abushwireb et al. [98] showed that the designed extractive distillation schemes meet all expectations regarding energy consumption and cuts purity. The economic analysis presented in their report proved that the heat-integrated extractive distillation configuration is the best candidate compared to Petlyuk column, divided-wall column and conventional column.

4.3. Heat integrated pressure-swing distillation for close-boiling mixture separation

To fractionate a binary close-boiling mixture, three techniques are commonly used [99]: azeotropic distillation, extractive distillation and pressure-swing distillation (PSD). These all three schemes have very similar process flowsheet. In the first two approaches, a third component called solvent is used to enhance the relative volatility of the components to be separated. The use of a solvent involves several drawbacks, such as [100]: (i) since the solvent can never be completely removed, it adds an unexpected impurity to the products, (ii) solvent recovery cost may be large enough, (iii) there may be inevitable loss of solvent, and (iv) it may cause serious environmental concerns.

For the above problems associated with the azeotropic and extractive distillations, the PSD approach has emerged as an attractive alternative [101–103]. A prerequisite for the use of PSD column is that the azeotrope separated must be pressure sensitive. In this separation scheme, a low-pressure (LP) and high-pressure (HP) distillation columns are combined to avoid the azeotropic point.

Since the PSD configuration includes a HP and a LP distillation columns, a possibility of heat integration arises. Two kinds of energy integration for PSD processes are reported in literature [104]. One is the condenser/reboiler type heat integration, in which the condenser of the HP distillation column is integrated with the reboiler of the LP distillation process. The second one is the rectifying/stripping section type heat integration, in which the rectifying section of the HP distillation unit is coupled with the stripping section of the LP distillation unit. To separate the close-boiling mixtures, the latter is economically superior to the former and for other mixtures separation, the reverse is true [104]. Both the condenser/reboiler type [105,106] and rectifying/stripping section type [104,107,108] heat integrated PSD columns have the potential of large energy savings for the separation of close-boiling mixtures.

4.4. Heat integrated cryogenic distillation

In general, the cryogenic distillation columns operate at extremely low temperatures. For example, to separate air in its basic components, oxygen and nitrogen [109], the cryogenic distillation process runs at around 100 K. At this low temperature, oxygen and nitrogen remain in liquid state and they can be separated in the column.

In the cryogenic separation unit, a very costly installation is arranged with the condenser if the overhead vapor is intended to convert to liquid-phase because the overhead vapor is enriched with more volatile component having very low boiling point. In order to reduce the energy cost, heat integration principle can be applied with coupling the reboiler and condenser in the cryogenic distillation configuration. Energy that is expelled in the condenser can be utilized in the reboiler.

Roffel et al. [110] proposed a heat integrated cryogenic distillation column (HICDiC) that is constructed with two smaller columns, keeping one above another, within a single distillation shell. The lower part of the distillation tower is the high-pressure column and the upper part the low-pressure column. Compressors are employed to elevate the pressure. The integrated reboiler–condenser unit displayed in Fig. 10 is positioned in the bottom of the LP column and just above the HP column. The difference in boiling points owing to the difference in pressure becomes the driving force for the transfer of heat in the integrated reboiler–condenser system. As shown in the figure, the vapor stream leaving the HP column condenses in the condenser and the liberated heat is used in the coupled reboiler to generate the vapor flow for the LP column. Here, the reboiler behaves just like a normal tray.

4.5. Reactive dividing wall column

Nowadays, process intensification has become a thrust area of research in chemical engineering and related disciplines because

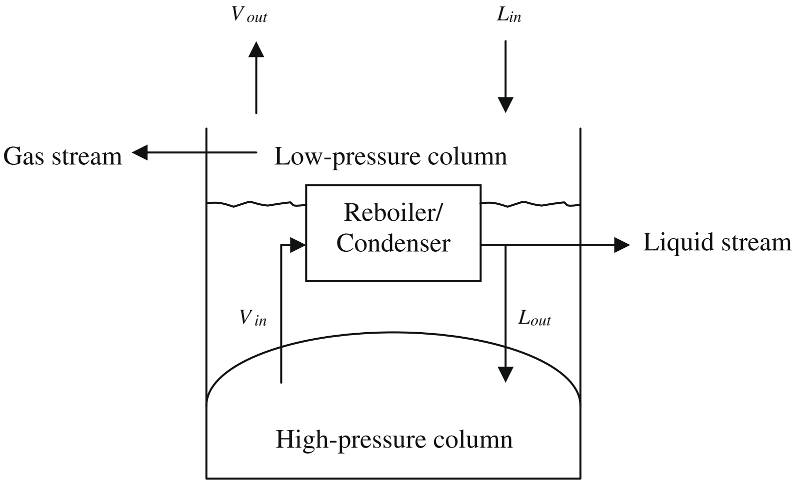

Fig. 10. A schematic representation of the reboiler–condenser system in a HICDiC structure.

it offers many potential advantages, such as: reduction in equipment size (low capital investment), improvements in process efficiency and safety, and decreased energy consumption (low operating cost). Reactive distillation and energy integrated distillation columns are the most important examples of process intensification in chemical engineering, although they represent two different ways of integration.

Mueller and Kenig [111] introduced a new integrated process by combining reactive distillation and dividing wall column. The resulting unit shown in Fig. 11 is called "reactive dividing wall column". The reactive zone can be considered in any one side of the wall or both sides. Since the structure displayed in the figure gives three high-purity product streams in a single column, it is suggested [111] to consider the following reactive systems:

(i) Reactive systems with more than two products (e.g., with consecutive and side reactions), which must be obtained as a pure fraction each.
(ii) Reactive systems with nonreacting components and with desired separation of both products and inert components.
(iii) Reactive systems having an excess of a reagent that should be separated with sufficient purity before being recycled.

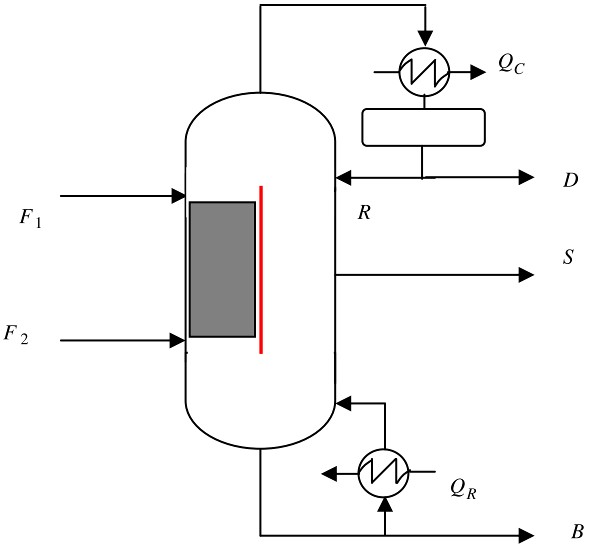

Fig. 11. A schematic representation of a reactive dividing wall distillation column.

4.6. Heat integration in naphtha reforming

Today, the demand of automobiles for high-octane gasolines has stimulated the use of catalytic reforming operation. Catalytic reformate furnishes approximately 30–40% of the US gasoline requirements [112]. It is worthy to mention that there exists a special need to restrict the aromatic contents of gasolines.

Naphtha reformate is extracted for aromatic compounds and the aromatics, mainly benzene, toluene and xylene, are separated into almost pure compounds. The separation is performed employing a series of binary-like conventional distillation units.

Recently, Lee et al. [113] explored the application of a fully thermally coupled distillation column (FTCDC) for fractionation process in naphtha reforming plant. In their study, the first two columns of the aromatic separation process in the reforming plant are replaced with a FTCDC, which is basically a two-column Petlyuk structure. The authors also showed that the FTCDC provides an energy saving of 13% and the investment cost reduction of 4% compared with a traditional two-column process.

4.7. Heat integration in crude distillation unit

Carbon dioxide, a greenhouse gas, plays an important role in global warming. It contributes about two-thirds of the enhanced greenhouse effect [114,115]. Studies show that a significant contribution to the CO_2 emitted to the environment is attributed to fossil fuel combustion, which accounts for around 98% of total CO_2 emissions in the US for the year 1999 [116] and 95% of total CO_2 emissions in the UK for the year 2000 [115,117]. In order to meet the environmental regulations as agreed in the Kyoto Protocol [118], the chemical process industries require capital-intensive technology to decrease the greenhouse gas, particularly CO_2, emissions.

As stated earlier, it is a fact that there is a strong relation between energy consumption in distillation and CO_2 gases produced in the atmosphere. The higher the energy demands are, the larger the CO_2 emissions to the atmosphere are. Crude fractionation units probably produce more CO_2 to the environment than other distillation processes. Sources of CO_2 emissions from utility systems (e.g., turbine, furnace and boiler) of a typical crude distillation unit (CDU) are presented in Fig. 12. In the following, few important techniques [115] are highlighted for improving energy efficiency of crude oil distillation units.

(i) The energy efficiency can be enhanced by the reduction of heat load on the furnace installing intermediate reboilers in crude towers [119].

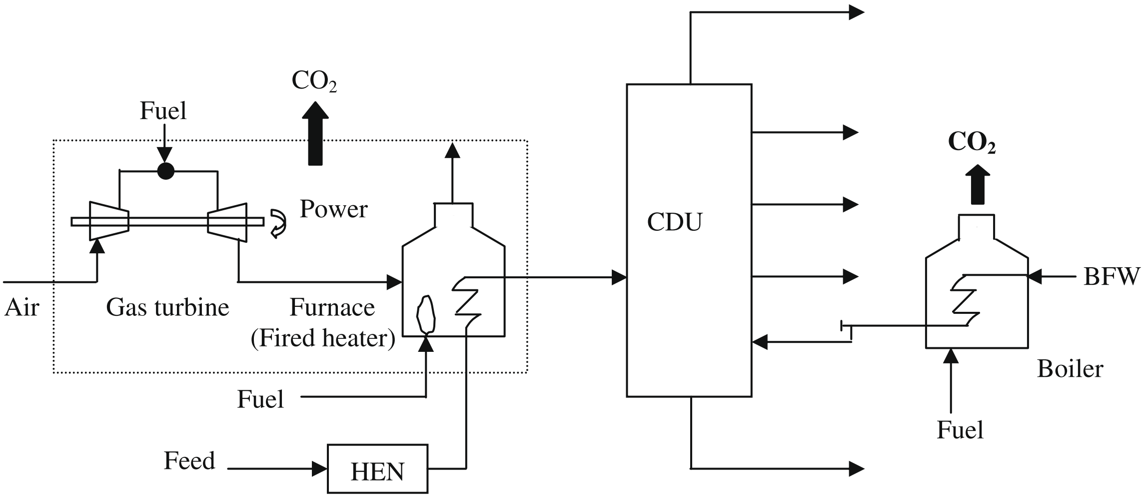

Fig. 12. Sources of CO$_2$ emissions from a CDU [141] (HEN: heat exchanger network, BFW: boiler feed water).

(ii) By the use of preflash or prefractionator units to existing crude distillation towers, a good amount of energy saving can be achieved in the furnace [120].
(iii) It is possible to save energy using more trays in existing CDUs and strippers as well as reboilers in stripping columns [121].
(iv) Energy efficiency can be improved by minimizing the flue gas emissions from utility systems through changing fuels or utility system design, improved heat recovery, and chemical treatment of flue gases [122].
(v) The flue gas emissions and hence the operational costs can be sharply reduced by integrating a gas turbine with an existing refinery site [123].
(vi) By optimizing the process conditions, Gadalla et al. [115] showed that existing crude oil installations can save up to 21% in energy and 22% in emissions. Additionally, by integrating a gas turbine with the crude tower, the total emissions can be reduced further by 48%.

At this point, it is appropriate to mention that along with the development of energy integration technology, research attention must be paid on alternative fuels [124,125] that contribute reduced greenhouse gas.

5. Improved structures of HIDiC scheme

As shown in Fig. 1, the heat integrated distillation column conventionally includes the trim-reboiler and trim-condenser. Although the reboiler as well as condenser is incorporated in the HIDiC structure, the heat load of them is remarkably lower than that of reflux condenser and bottom reboiler arranged in the conventional distillation process. In order to make the HIDiC structure more energy efficient, improved configurations of this structure have been explored subsequently and they are presented below.

5.1. Ideal HIDiC (i-HIDiC) scheme

Fig. 13 illustrates a schematic diagram of an i-HIDiC scheme that does not have both a reboiler and a condenser. Like other HIDiC configurations described below, it considers the thermal coupling between rectifying and stripping columns through a number of internal heat exchangers. To accomplish internal heat flow from one column to another, there is a need to make a difference in temperature between those columns. In order to have a temperature driving force, the rectifying section is operated at higher pressure than the stripping column. As mentioned, the pressure differential implies a corresponding differential in operating temperature. A compressor and a reducing valve are employed for this purpose.

The internal heat integration in a HIDiC leads to gradual evaporation along the length of the stripping section and gradual condensation along the length of the rectifying section. By this way, the reflux flow for the rectifying section and vapor flow for the stripping section are generated. Thus the condenser as well as the reboiler is not needed for the ideal HIDiC scheme, and both fixed and operating costs are reduced. Due to the absence of reboiler and condenser in the i-HIDiC scheme, the difficulty arises in operation, especially at start-up phase. To overcome this problem, Naito et al. [126] proposed a startup operation procedure. In that policy, the reboiler and condenser are in operation until the specified purity of distillate and bottom products are achieved. The compressor and throttling valve definitely play a vital role to reach at desired value. Finally, the products are started to withdraw with switching on the product composition (or tray temperature) controllers. Meanwhile, the reflux and reboil rates are gradually reduced to zero. As an alternative way, a feed preheater [3] can be installed as shown in the figure. In this preheater, the feed stream is heated up with an external heat source. But in this option, there is a high chance of inverse heat transfer from the stripping column to the rectifying column leading not only to consumption of extra energy but also risks of potential operation problems [126].

5.2. Intensified i-HIDiC (int-i-HIDiC) scheme

The intensified i-HIDiC scheme is configured with a slight modification of the i-HIDiC. Here the feed mixture is heated up before introducing into the stripping column. Since the overhead vapor is at high-pressure and high-temperature, it can be used as a potential heat source for the feed preheating. The resulting structure shown in Fig. 14 is called here as intensified i-HIDiC structure.

The int-i-HIDiC can be further modified under the name of int-i-HIDiC (L) and int-i-HIDiC (V) structures. The former configuration [28] displayed in Fig. 15 additionally includes an overhead condenser mainly to improve the controllability. The condenser and the feed preheater simultaneously take out the heat from the hot vapor distillate and consequently, the vapor is condensed and then accumulated in the reflux drum. This ideal HIDiC is known here as

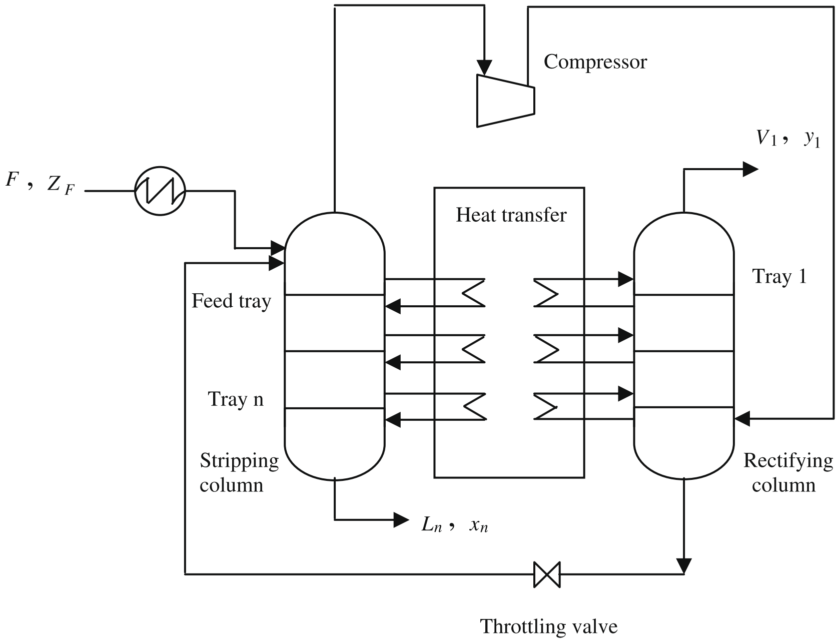

Fig. 13. A schematic representation of an i-HIDiC scheme.

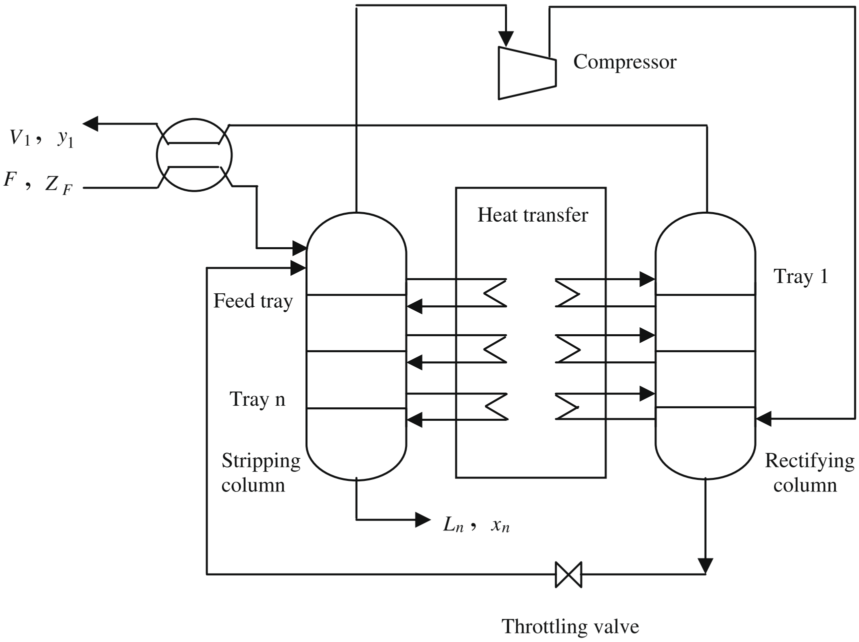

Fig. 14. A schematic representation of an intensified i-HIDiC scheme.

int-i-HIDiC (L) because the top product is discharged as a liquid (L) stream.

In the int-i-HIDiC (V) configuration depicted in Fig. 16, the feed stream first receives heat from the overhead vapor and then passes through a trim preheater before entering into the column. The distillate may be discharged from this intensified i-HIDiC as a vapor (V) stream and so possibly it is referred to as int-i-HIDiC (V) scheme.

Fukushima et al. [28] reported a comparative study between different HIDiC configurations along with conventional distillation column (CDiC) in terms of energy consumption in percentage basis (=100 × (energy consumed by any HIDiC/energy consumed by CDiC)). In their article, the percent energy consumptions of CDiC, HIDiC, i-HIDiC and int-i-HIDiC are given as 100%, 79%, 64.6% and 46.4%, respectively. It is obvious that the int-i-HIDiC configuration is most energy-efficient scheme. As stated previously, when the feed flow rate has increased above the designated value, the i-HIDiC is not economical and in such a situation, the general HIDiC is preferably used [3].

The HIDiCs are most promising separation structures, especially with regard to energy savings. But in return, these configurations involve extreme design complexity, operational difficulty and control problem. Although the HIDiC concept was introduced around 1970, it is still not implemented in industrial practice. Before com-

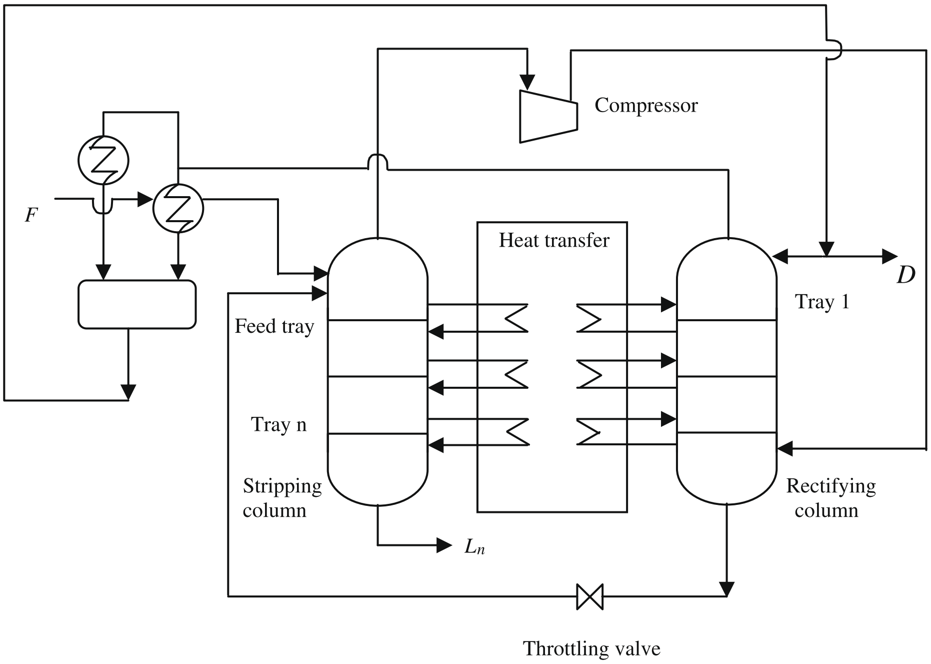

Fig. 15. A schematic representation of an intensified i-HIDiC (L) scheme.

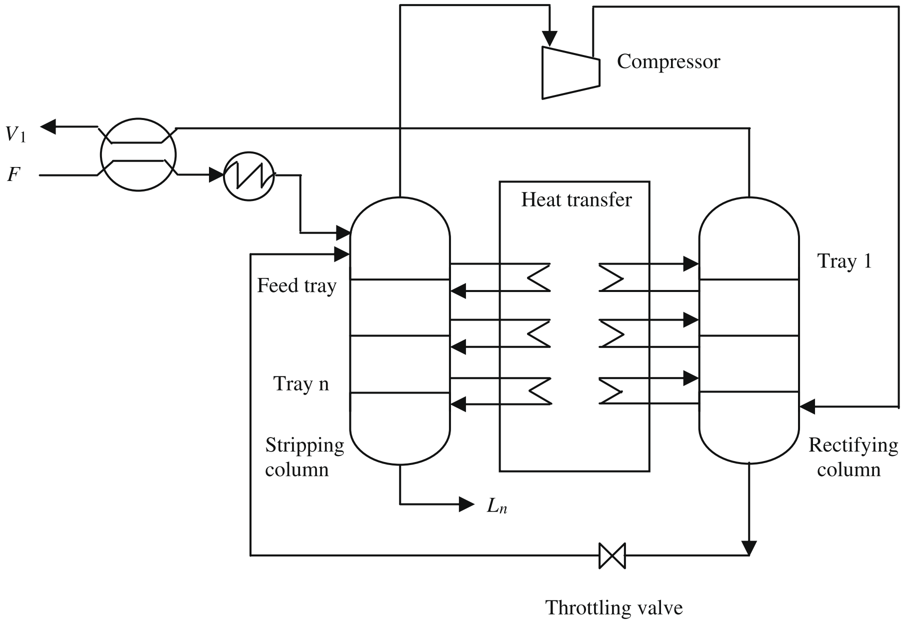

Fig. 16. A schematic representation of an intensified i-HIDiC (V) scheme.

mercializing the HIDiC technology, there is a special need to improve further the HIDiC structure. The following discussion focuses on several issues for improvement.

6. HIDiC: future research issues

6.1. Process modeling

The development of mathematical model for a heat integrated distillation column, like other processes, is needed for many reasons, such as to understand the column dynamics, to estimate the imprecisely known process parameters, to synthesize the model-based controllers, etc. Therefore, attention must be given to construct a rigorous model structure so that it can predict the process characteristics precisely.

A detailed first-principles model of HIDiC would include the variable liquid holdup on each tray, energy balance, nonideal stage behavior, pressure drop across each stage and nonlinear Francis weir formula for tray hydraulics. In addition, it is very much needed to incorporate a thermodynamic model, to represent the phase nonideality, in the HIDiC model structure because of high pressure distillation, especially rectification operation, and nonideal feed mixture. The effects of phase nonideality on the i-HIDiC characteristics are rarely reported in literature.

A limited number of papers (e.g. [27,34,127]) consider the fundamental modeling and the simulation of practical i-HIDiC structures. Recently, Fukushima et al. [28] and Kano et al. [128] developed a rigorous simulator for the i-HIDiC using the Aspen Custom Modeler. In addition to the improvement of equilibrium-based i-HIDiC model incorporating the suggestions pointed out above, it is also required to pay more effort for the development of rate-based model, empirical model including ANN-based model and hybrid (combination of empirical and first-principles) model.

It is worthy to mention that once the simulated model is ready, it should be experimentally validated under different realistic situations. Then only the rigorous model is appropriate to use for optimal process configuration based on parametric sensitivity, process dynamics prediction, theoretical analysis of multiple steady states, model-based controller design, and so on.

6.2. Optimal design

It is realized that the HIDiC offers an appealing advantage of large energy savings compared to the conventional and some nonconventional distillation (e.g., VRC) columns at the cost of an increased capital investment due to the compressor and the increased complexity of the column. Obviously, there arises a need for designing the optimal HIDiC configuration so that the total annual cost (TAC) is reasonably low.

In this article, we have categorized the HIDiC into different schemes. These configurations again make difference over the conventional distillation mainly due to the heat integration arrangement and inclusion of reflux condenser and/or reboiler. This difference in configuration may cause new considerations on HIDiC design.

In designing a HIDiC structure, some important points presented below need to be taken into account.

- It is required to design the HIDiC with changing the diameter along the height of both the stripping and rectifying sections because the cross sectional area of the column is proportional to the vapor flow rate [126]. In the rectifying column, the vapor is condensed gradually along the length and consequently, the vapor flow rate decreases as it moves from the bottom to the top. On the contrary, in the stripping section, the liquid evaporates gradually along the column length and the vapor flow rate increases as it goes upward. A typical cross section of a practical HIDiC is shown in Fig. 17.
- From energy saving viewpoint, it is always expected to have a small temperature difference between the thermally coupled rectifying and stripping sections [129]. Therefore, in order to achieve good separation, the design of the HIDiC should be such that it meets the requirement of large heat transfer area per tray.
- It is well-known that to fractionate a close-boiling mixture, a large reflux ratio is allowed to obtain the desired product purity. Again, the heat integrated distillation columns are relatively small in diameter due to the increased density of vapor at high pressure. In practice, it is difficult to handle a large liquid flow in a small diameter HIDiC filled with packing material. Hence, for sufficiently high pressure operation, the use of tray-type HIDiC design is suggested [130].
- In some cases, for example, when the feed flow rate is higher than the designated value and when the high-purity products are expected, there is a need of high compression ratio (pressure in rectifying column/pressure in stripping column). As a result, the advantage of the HIDiC with respect to energy savings is totally lost because the electricity required to operate the compressor is several times more expensive than the heating steam required for the reboiler. Therefore, it is recommended to use the general HIDiC that accompanies trim-reboiler and/or trim-condenser when the high compression ratio is required in the distillation operation.

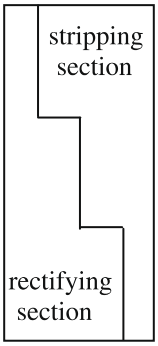

Fig. 17. A typical cross section of a practical HIDiC scheme.

A systematic design approach for the HIDiC as well as CDiC is devised [31] as an iterative procedure. In designing a column, the ultimate aim is to minimize the total annual cost that is the sum of operating cost (OC) and annual capital investment. The capital investment (CI) includes the cost of equipments (distillation column, heat exchangers and compressors) and the operating cost includes the cost of utilities (heating steam, cooling water and electricity). The annual capital investment is calculated by dividing the CI by payback period (*T*), which is CI/T. Douglas [131] reported the cost estimation formulas for distillation equipments and Nakaiwa et al. [3] discussed the cost indices for utilities. It is suggested [31] to add a penalty of 20% for the HIDiC because of the difficulty involved in installation of internal heat transfer arrangements.

This recursive design technique aims to keep the TAC minimum with determining the total number of trays through iteration. Usually, the payback period of 3 years is assumed in cost estimation for HIDiC structure. However, Nakaiwa et al. [3] calculated the payback time of 2.78 years for a bench-scale plant. Special emphasis must be paid for better designing of HIDiC scheme so that the payback period is further reduced.

6.3. Multiple steady states

The existence of multiple steady states (MSS) increases the difficulties in operation and control. From a control perspective, the multiplicities can be classified into two categories: output multiplicity and input multiplicity. The former implies to multiple output values for the same input specification while the latter implies to multiple input specifications giving the same output. With reference to control schemes, input variables are those that can be manipulated by control valves or other actuating devices and output variables are those that are either controlled or measured to describe the process.

Multiple steady states in conventional distillation have been known from simulation studies dating back to the 1970s. However, in the last year, Hasebe and his research group [128] first introduced the concept of MSS in a heat integrated distillation column, in which the heat was transferred from the rectifying section to the stripping section through a divided wall. The first-principles model was used for the multiplicity analysis. The authors observed that the instability condition depends largely on the compressor operation policies.

The existence of multiple steady states is a research area of HIDiC that is only beginning to be explored. The MSS analysis provides useful information for selecting control scheme, operation policy, operating conditions and process design. It is notable that a suitable control law needs to be devised with proper controlled variable–manipulated variable pairing to stabilize an open-loop unstable column. Also, for a process having multiple steady states, special care has to be taken during column startup to get the column close to the desired steady state.

6.4. System identification

For designing a HIDiC scheme, one of the key steps is to find the optimal operation parameters, such as the pressure of rectifying section and feed thermal condition. Liu and Qian [34] proposed first time an optimization model of i-HIDiC operation parameters for obtaining the optimal parameter values under steady state condition to ensure not only the product quality and the maximum energy savings but also the operability and controllability. In their study, the sample column provided smooth closed-loop response with PID controllers and the steady state operation optimization met the i-HIDiC optimization needs.

However, the parameter values obtained by solving steady state optimization problem may not provide satisfactory performance at transient state and even may cause closed-loop instability [34]. To avoid this uncertain circumstance, either an advanced control policy should be devised to improve the operation stability or the dynamic optimization problem must be solved. In the subsequent discussion, the demand of advanced nonlinear control laws for the HIDiC is presented. Up to now, no one has solved the dynamic optimization case for finding the optimal operation parameter values.

6.5. Advanced nonlinear control

Before designing a control system for closed-loop performance of a HIDiC scheme, it is important to select the best possible control pairs. In this regard, some progress is noted in the literature papers. For example, Roffel et al. [110] and Zhu and Liu [132] selected the suitable pairings on the basis of relative gain array (RGA) method. Fukushima et al. [28] listed in Table 3 of their article the possible control loops and corresponding relative gain value for the conventional distillation, HIDiC, i-HIDiC, int-i-HIDiC and int-i-HIDiC (L) structures.

Like conventional distillation column, the primary control objective of the HIDiC is to maintain the quality of the top and bottom products at their specified values. Direct composition control of the HIDiC structures is presented by several researchers (e.g. [27,31,34]). However, temperature control, instead of composition control, may be preferred because the composition analyzers are expensive, require high maintenance and introduce dead-time into the control loop. It is important to mention that the selection of the trays to temperature control is one of the important issues in closed-loop study. Recently, a novel temperature control system for the i-HIDiC is presented by Huang et al. [133]. Emphasis must be given to explore the advanced temperature control schemes.

As an alternative to the composition controller, one may design an inferential soft sensor based control strategy. In this scheme, the product compositions of the column to be controlled can be inferred using the suitable secondary measurements (e.g., multiple temperatures). The soft sensor can be developed by using multivariable regression technique [134,135], artificial neural networks [136], direct process model [137], and few other techniques. For binary systems, the design approach of soft sensing device is available [27,137]. Also, Quintero-Marmol et al. [138] developed a composition soft sensor for an ideal ternary system. The main concern is that the inaccuracy level may be significant in the product compositions computed by a soft sensor. Therefore, before using a soft sensor in the inferential control structure, it is must to ensure the precise prediction of composition dynamics provided by the sensor.

Very few literature papers considered the closed-loop control of heat integrated distillation columns. Perhaps all of them available so far deal with the linear control schemes including proportional integral (PI) or proportional integral derivative (PID) controllers (e.g. 27,28,31,34,133]) and internal model controller (IMC) [132].

When reflux condenser and bottom reboiler are incorporated within the heat integrated distillation tower, the control configuration can be the same as conventional distillation unit. As mentioned, an ideal heat integrated distillation column that involves heat integration between the rectifying and stripping sections is designed without a reboiler and condenser. Although, this structure has the potential of large energy savings but it leads to complicated dynamics. Because of its higher degree of thermal coupling between two sections, interactions are likely to be significantly intensified. It is suspected [139] that thermal interaction may lead to an unstable process which is quite difficult to operate by the conventional PID controller.

In addition to the internal heat integration between the rectifying and stripping columns, there exists another heat integration between the overhead product and feed flows within the int-i-HIDiC, int-i-HIDiC (L) and int-i-HIDiC (V) schemes. These two heat integrations interact with each other and consequently, process operation is further complicated. It has been proven that the intensified i-HIDiC has originally a pole at the origin of the complex plane and therefore becomes an open-loop integrating process [140]. Actually, an internal heat recycle is created in the int-i-HIDiC structures and is quite likely to lead to an open-loop unstable process, thereby deteriorating process controllability and posing a more challenging problem [31]. This situation can only be efficiently tackled by the use of a high-quality control methodology. Therefore, we need to judge whether the heat integration should be permitted up to a certain level so that the system remains open-loop stable or the open-loop instability problem due to complete heat integration must be resolved by means of advanced control system.

Due to the complex dynamics, it is very difficult to develop a linear model that can predict the HIDiC behavior precisely. Consequently, there exists a plant/model mismatch that limits the application of some linear model-based control strategies, such as IMC structure, especially in high-purity systems. To obtain a satisfactory closed-loop performance, therefore, it is required to employ an advanced nonlinear multivariable control law (e.g., nonlinear model predictive controller, globally linearizing controller and sliding mode controller) around the strongly nonlinear interactive heat integrated distillation columns. Based of our knowledge, there is no research work published presenting the advanced nonlinear control of the heat integrated distillation columns.

6.6. Experimental evaluation

Although the heat integrated distillation column was proposed a long back, very few real-time testing have been reported so far. An experimental study on i-HIDiC was first conducted in 2000 [126] for the separation of a benzene–toluene mixture. The work of Naito et al. [126] includes process operation at startup and normal conditions with and without external reflux and reboil flows. Energy saving by the use of i-HIDiC setup was also proved in their study. A single article is available for binary mixture separation, and no experimental work is reported so far for the separation of a multicomponent mixture.

Before going for commercialization of the HIDiC technology, the theoretical predictions must be confirmed by performing experiments in different scales. There is a need to conduct a series of experiments to examine the operation feasibility, actual energy savings, overall cost and control performance. Exploring the economical and operational feasibility, a decision would be taken in case-to-case basis whether the existing conventional distillation columns can be modified (or replaced) to the HIDiC schemes or the application of the new heat integration technique will only be limited to the upcoming plants.

6.7. Proposed applications of heat integration concept

As discussed earlier, the heat integration principle has been successfully applied in many distillation operations, such as extractive distillation, batch distillation, cryogenic distillation and crude distillation. Further research effort needs to be placed on developing other thermally coupled distillation columns.

Reactive distillation is an innovating process which realizes both distillation and chemical reaction into a solely unit. It enjoys many potential advantages over separate distillation plus reaction processes, such as higher conversion, reduced capital cost, improved selectivity, lower energy consumption, scope for difficult separations, avoidance of azeotropes, and many others. Very recently [111], a divided wall reactive distillation column has been proposed. To improve the energy efficiency, attention must be given to develop the heat integrated reactive distillation column (HIRDiC). In the development of HIRDiC structure, care must be taken to meet the key restrictions of reactive distillation technology. The main restrictions include:

(1) The necessary conditions for the reaction must match those of distillation.
(2) The relative volatility of reactants and products should be such that high concentration of reactants and low concentration of products can be maintained in the reactive zone.
(3) It is therefore suggested to explore the design and operation feasibility of HIRDiC.

The application can also be extended to a process, in which, two distillation columns that are not directly connected can be thermally coupled. This idea can be implemented in a wide variety of processes.

7. Conclusions

In the present review, several thermally coupled distillation structures have been presented. Recently, the heat integration principle has been applied on some complex separation schemes, including crude distillation. In this article, the main attention is focused on most promising energy-efficient HIDiC operation and its improved forms, namely i-HIDiC, int-i-HIDiC, int-i-HIDiC (L) and int-i-HIDiC (V).

Over the last few decades, the heat integration principle emerged which allows researchers to address problems like energy savings, process design, operation feasibility, etc. But all these issues are understood for simulated thermally coupled distillation columns. Although the HIDiC concept was introduced around 1970, it is still at the primary stage of research from practical viewpoint and not commercialized so far for industrial application. To improve the HIDiC technology, several research gaps and future priorities have been identified in this review paper. It is also important that the application of heat integration principle to other distillation processes, such as reactive distillation and two distillation columns having no direct connection, needs to be explored.

References

[1] Humphrey JL, Siebert AF. Separation technologies: an opportunity for energy savings. Chem Eng Prog 1992(March):92.
[2] Engelien HK, Skogestad S. Selecting appropriate control variables for a heat-integrated distillation system with prefractionator. Comput Chem Eng 2004;28:683–91.
[3] Nakaiwa M, Huang K, Endo A, Ohmori T, Akiya T, Takamatsu T. Internally heat-integrated distillation columns: a review. Trans IChemE 2003;81:162–77.
[4] Brugma AJ. Dutch patent 41,850; 1937.
[5] Wright RO. Fractionation apparatus. US patent 2,481,134; 1949.
[6] Petlyuk FB, Platonoy VM, Slavinskii DM. Thermodynamically optimal method for separating multicomponent mixtures. Int Chem Eng 1965;5:555–61.
[7] Freshwater DC. Thermal economy in distillation. Trans Inst Chem Eng 1951;29:149–60.
[8] Freshwater DC. The heat pump in multicomponent distillation. Trans Inst Chem Eng 1961;6:388–91.
[9] Flower JR, Jackson R. Trans Inst Chem Eng 1964;42:249–58.
[10] Null HR. Heat pumps in distillation. Chem Eng Prog 1976;73:58–64.
[11] King CJ. Separation processes. 2nd ed. New York: McGraw-Hill; 1980. p. 680–9.
[12] Smith R. Chemical process design. 1st ed. New York: McGraw-Hill; 1995. p. 341–53.
[13] Alarcón-Padilla D-C, García-Rodríguez L. Application of absorption heat pumps to multi-effect distillation: a case study of solar desalination. Desalination 2007;212:294–302.
[14] Aristov YI, Dawound D, Glaznev IS, Elyas A. A new methodology of studying the dynamics of water sorption/desorption under real operating conditions of adsorption heat pumps: experiment, Int J Heat Mass Transfer. doi:10.1016/j.ijheatmasstransfer.2007.10.042.
[15] Haselden GG. An approach to minimum power consumption in low temperature gas separation. Trans Inst Chem Eng 1958;36:123–32.
[16] Mah RSH, Nicholas JJ, Wodnik RB. Distillation with secondary reflux and vaporization: a comparative evaluation. AIChE J 1977;23:651–7.
[17] Fitzmorris RE, Mah RSH. Improving distillation columns design using thermodynamic availability analysis. AIChE J 1980;26:265–73.
[18] Wang JC, Henke GE. Tridiagonal matrix for distillation. Hydrocarb Process 1966;45:155–63.
[19] Shimizu K, Mah RSH. Dynamic characteristics of binary SRV distillation systems. Comput Chem Eng 1983;7:105–22.
[20] Shimizu K, Holt BR, Morari M, Mah RSH. Assessment of control structures for binary distillation columns with secondary reflux and vaporization. Ind Eng Chem Process Des Dev 1985;24:852–8.
[21] Nakaiwa M, Owa M, Akiya T, Kawasaki S, Lueprasitsakul V, Yajima K, et al. Kagaku Kogaku Ronbun 1986;12:535–41.
[22] Takamatsu T, Lueprasitsakul V, Nakaiwa M. Modeling and design method for internal heat-integrated packed distillation column. J Chem Eng Jpn 1988;21:595–601.
[23] Lueprasitsakul V, Hasebe S, Hashimoto I, Takamatsu T. Study of energy efficiency of a wetted-wall distillation column with internal heat integration. J Chem Eng Jpn 1990;23:580–7.
[24] Lueprasitsakul V, Hasebe S, Hashimoto I, Takamatsu T. Analysis of the characteristics of a binary packed distillation column with internal heat integration. J Chem Eng Jpn 1990;23:686–91.
[25] Takamatsu T, Nakaiwa M, Nananishi T. The concept of an ideal heat integrated distillation column (HIDiC) and its fundamental properties. Kagaku Kogaku Ronbun 1996;22:985–90.
[26] Takamatsu T, Nakaiwa M, Nananishi T, Aso K. Possibility of energy saving in the ideal heat integrated distillation column (HIDiC). Kagaku Kogaku Ronbun 1997;23:28–36.
[27] Huang K, Nakaiwa M, Akiya T, Aso K, Takamatsu T. A numerical consideration on dynamic modeling and control of ideal heat integrated distillation columns. J Chem Eng Jpn 1996;29:344–51.
[28] Fukushima T, Kano M, Hasebe S. Dynamics and control of heat integrated distillation column (HIDiC). J Chem Eng Jpn 2006;39:1096–103.
[29] Kjelstrup RS, Sauar E, Hansen EM, Lien KM, Hafskjold B. Analysis of entropy production rates for design of distillation columns. Ind Eng Chem Res 1995;34:3001–7.
[30] Aguirre P, Espinosa J, Tarifa E, Scenna N. Optimal thermodynamic approximation to reversible distillation by means of interheaters and intercoolers. Ind Eng Chem Res 1997;36:4882–93.
[31] Huang K, Shan L, Zhu Q, Qian J. Design and control of an ideal heat-integrated distillation column (ideal HIDiC) system separating a close-boiling ternary mixture. Energy 2007;32:2148–56.
[32] Rivera-Ortega P, Picón-Núñez M, Torres-Reyes E, Gallegos-Muñoz A. Thermal integration of heat pumping systems in distillation columns. Appl Therm Eng 1999;19:819–29.
[33] Iwakabe K, Nakaiwa M, Nakanishi T, Huang K, Zhu Y, Røsjorde A. Analysis of the energy savings by HIDiC for the multicomponent separation. APPChE, 0259, Kitakyushu, Japan; 2004.

[34] Liu X, Qian J. Modeling, control, and optimization of ideal internal thermally coupled distillation columns. Chem Eng Technol 2000;23:235–41.

[35] Takamatsu T, Nakaiwa M, Aso K. Japanese patent no. 3184501; 1990.

[36] Aso K, Matsuo H, Noda H, Takada T, Kobayashi N. Heat integrated distillation column. US patent 5783047; 1998.

[37] Aso K, Matsuo H, Noda H, Takada T, Kobayashi N. Internal heat exchange type distillation column. European patent EP0726085; 2002.

[38] Aso K, Nakanishi T, Nakaiwa M, Takamatsu T. Heat integrated distillation column. European patent EP1380328; 2007.

[39] De Graauw J, de Rijke A, Olujic Z, Jansens PJ. Heat integrated distillation column. European patent EP1332781; 2003.

[40] De Graauw J, Steenbakker MJ, de Rijke A, Olujic Z, Jansens PJ. Distillation column with heat integration. European patent EP1476235; 2004.

[41] De Graauw J, Steenbakker MJ, de Rijke A, Olujic Z, Jansens PJ. Heat integrated distillation column. US patent US2005121303; 2005.

[42] Brown D. Simulations of equal thermodynamic distance distillation columns for regular solutions. Master Thesis, San Diego State University, San Diego; 1998.

[43] Salamon P, Nulton JD. The geometry of separation processes: a horse–carrot theorem for steady flow systems. Europhys Lett 1998;42:571–6.

[44] Schaller M. Numerically optimized diabatic distillation columns. PhD Thesis, Technische Universitat Chemnitz, Fakultat fur Naturwissenschaften; 2007.

[45] Humphrey JL, Seibert AF, Koort RA. Separation technologies advances and priorities. Final report for US Department of Energy, Office of Industrial Technologist, Washington (DC); 1991.

[46] De Koeijer G, Kjelstrup S. Minimizing entropy production rate in binary tray distillation. Int J Appl Thermodyn 2000;3:105–10.

[47] Wolff EA, Skogestad S. Operation of integrated three-product (Petlyuk) distillation columns. Ind Eng Chem Res 1995;34:2094–103.

[48] Kaibel G. Distillation columns with vertical partitions. Chem Eng Technol 1987;10:92.

[49] Triantafyllou C, Smith R. The design and optimisation of fully thermally coupled distillation columns. Trans Inst Chem Eng 1992;70:118–32.

[50] Seader JD. Continuous distillation apparatus and method. US patent 4,234,391; 1980.

[51] Seader JD, Baer SC. Continuous distillation apparatus and method. Final report, University of Utah, Salt Lake City; 1984.

[52] Agrawal R. Multicomponent distillation columns with partitions and multiple reboilers and condensers. Ind Eng Chem Res 2001;40:4258–66.

[53] Adrian T, Schoenmakers H, Boll M. Model predictive control of integrated unit operations: control of a divided wall column. Chem Eng Process 2004;43:347–55.

[54] Cahn RP, Di Micelli AG. US patent 3,058,893; 1962.

[55] Stupin WJ, Lockhart FJ. Thermally coupled distillation – a case history. Chem Eng Prog 1972;68:71–2.

[56] Cerda J, Westerberg AW. Shortcut methods for complex distillation columns. 1. Minimum reflux. Ind Eng Chem Process Des Dev 1981;20:546–57.

[57] Halvorsen IJ, Skogestad S. Optimal operation of Petlyuk distillation: steady state behavior. J Proc Control 1999;9:407–24.

[58] Shah PB. Squeeze more out of complex columns. Chem Eng Prog 2002;98:46–55.

[59] Al-Elg AH, Palazoglu A. Modeling and control of a high-purity double-effect distillation column. Comput Chem Eng 1989;13:1183–7.

[60] Ophir A, Gendel A. Adaptation of the multi-effect distillation (MED) process to yield high purity distillate for utilities, refineries and chemical industry. Desalination 1994;98:383–90.

[61] Han M, Park S. Multivariable control of double-effect distillation configurations. J Proc Control 1996;6:247–53.

[62] Hasebe S, Noda M, Hashimoto I. Optimal operation policy for total reflux and multi-effect batch distillation systems. Comput Chem Eng 1999;23:523–32.

[63] Cheng HC, Luyben WL. Heat-integrated distillation columns for ternary separations. Ind Eng Chem Process Des Dev 1985;24:707–13.

[64] Emtir M, Rev E, Fonyo Z. Rigorous simulation of energy integrated and thermally coupled distillation schemes for ternary mixture. Appl Therm Eng 2001;21:1299–317.

[65] Finelt S. Better C_3 distillation pressure. Hydrocarb Process 1979;58:95–8.

[66] Menzies MA, Johnson AI. Steady-state modeling and parametric study of a vapor recompression unit. Can J Chem Eng 1981;59:487–91.

[67] Meili A. Heat pumps for distillation columns. Chem Eng Prog 1990:60–5.

[68] Mostafa HA. Thermodynamic availability analysis of fractional distillation with vapor recompression. Can J Chem Eng 1981;59:487–91.

[69] Quadri GP. Use of heat pump in P–P splitter, part 1: process design. Hydrocarb Process 1981;60:119–26.

[70] Quadri GP. Use of heat pump in P–P splitter, part 2: optimization. Hydrocarb Process 1981;60:147–51.

[71] Flores J, Castells F, Ferre JA. Recompression saves energy. Hydrocarbon Process 1984;63:59–62.

[72] Muhrer C, Collura MA, Luyben WL. Control of vapor recompression distillation columns. Ind Eng Chem Res 1990;29:59–71.

[73] Canales ER, Marquez FE. Operation and experimental results on a vapor recompression pilot plant distillation column. Ind Eng Chem Res 1992;31:2547–55.

[74] De Rijke A. Development of a concentric internally heat integrated distillation column. PhD Thesis, Technische Universiteit Delft, The Netherlands; 2007.

[75] Fonyo Z. Thermodynamic analysis of rectification I. Reversible model of rectification. Int Chem Eng 1974;14:18–27.

[76] Fonyo Z. Thermodynamic analysis of rectification II. Finite cascade models. Int Chem Eng 1974;14:203–10.

[77] Rivero R. L'analyse d'exergie: application a la distillation et aux pompes a chaleur a absorption. PhD Thesis, Institut National Polytechnique de Lorraine, Nancy, France; 1993.

[78] Le Goff P, Cachot T, Rivero R. Exergy analysis of distillation processes. Chem Eng Technol 1996;19:478–85.

[79] De Koeijer G, Rosjorde A, Kjelstrup S. Distribution of heat exchange in optimum diabatic distillation columns. Energy 2004;29:2425–40.

[80] Markus S. Numerically optimized diabatic distillation columns. PhD Thesis, Technische Universitat Chemnitz, Fakultat fur Naturwissenschaften; 2007.

[81] Sun L, Olujic Z, De Rijke A, Jansens PJ. Industrially viable configurations for a heat-integrated distillation column, better processes for bigger profits. In: Proceedings of 5th international conference on process intensification for the chemical industry, Maastricht, The Netherlands; 2003.

[82] Vaselenak JA, Grossmann IE, Westerberg AW. Heat integration in batch processing. Ind Eng Chem Process Des Dev 1986;25:357–66.

[83] Takamatsu T, Tajiri A, Okawa K. In: Proceedings of the chemical engineering conference of Japan, Nagoya; 1998. p. 628–9.

[84] Haselden GG. Distillation processes and apparatus. US patent 4,025,398; 1977.

[85] Beggs S. Meng project report. UK: University of Edinburgh; 2002.

[86] Kaeser M, Pritchard CL. Heat transfer at the surface of sieve trays, In: Proceedings of the UK heat transfer 2003 Session, 2003.

[87] Govind R. Distillation column and process. US patent 4,615,770; 1986.

[88] Govind R. Dual distillation columns. US patent 4,681,661; 1987.

[89] Glenchur T, Govind R. Study on a continuous heat integrated distillation column. Sep Sci Technol 1987;22:2323–38.

[90] De Graauw J, Steenbakker MJ, De Rijke A, Olujic Z, Jansens PJ. Distillation column with heat integration. Dutch patent P56921NL00; 2003.

[91] Aso K, Takamatsu T, Nakaiwa M. Heat integrated distillation column. US patent 5,873,047; 1998.

[92] Mah RSH. Performance evaluation of distillation systems. Proc Found Comput Aided Chem Process Des 1980;2:171–202.

[93] Tung H-H, Davis JF, Mah RSH. Fractionating condensation and evaporation in plate-fin devices. AIChE J 1986;32:1116–24.

[94] Aitken WH. Apparatus for combined heat and mass transfer. US patent 5,722,258; 1998.

[95] Hugill JA. System for stripping and rectifying a fluid mixture. International patent application WO 03/011418 A1, assigned to ECN; 2003.

[96] Hugill JA, van Dorst EM. The use of compact heat exchangers in heat-integrated distillation columns. In: Proceedings of fifth international conference on enhanced, compact and ultra-compact heat exchangers: science, engineering and technology, Whistler, Canada; 2005.

[97] Iwakabe K, Nakaiwa M, Huang K, Nakanishi T, Røsjorde A, Ohmori T. Performance of an internally heat-integrated distillation column (HIDiC) in separation of ternary mixtures. J Chem Eng Jpn 2006;39:417–25.

[98] Abushwireb F, Elakrami H, Emtir M. Recovery of aromatics from pyrolysis gasoline by conventional and energy-integrated extractive distillation. Comput Aided Chem Eng 2007;24:1071–6.

[99] Hoffman EJ. Azeotropic and extractive distillation. 1st ed. New York: John Wiley & Sons, Inc.; 1964.

[100] Treybal RE. Mass-transfer operations. 3rd ed. Singapore: McGraw-Hill; 1980.

[101] Knapp JP, Doherty MF. A new pressure-swing distillation process for separating homogeneous azeotropic mixtures. Ind Eng Chem Res 1992;31:346–57.

[102] Horwitz BA. Optimize pressure-sensitive distillation. Chem Eng Prog 1997;93:47–51.

[103] Frank TC. Break azeotropes with pressure-sensitive distillation. Chem Eng Prog 1997;93:52–63.

[104] Huang K, Shan L, Zhu Q, Qian J. Adding rectifying/stripping section type heat integration to a pressure-swing distillation (PSD) process. Appl Therm Eng 2008;28:923–32.

[105] Knapp JP, Doherty MF. Thermal integration of homogeneous azeotropic distillation sequences. AIChE J 1990;31:969–84.

[106] Repke JU, Klein A, Forner F. Homogeneous azeotropic distillation in an energy- and mass-integrated pressure swing column system. Comput Aided Chem Eng 2004;18:757–62.

[107] Nakaiwa M, Huang K, Iwakabe K, Endo A, Ohmori T, Yamamoto T, et al. External heat-integration for ternary mixture separation. In: Proceedings of 18th international conference on efficiency, cost, optimization, simulation, and environmental impact of energy systems (ECOS 2005), vol. 3; 2005. p. 1279–86.

[108] Schmal JP, Van Der Kooi HJ, De Rijke A, Olujic Z, Jansens PJ. Internal versus external heat integration: operational and economical analysis. Chem Eng Res Des 2006;84:374–80.

[109] Mandler JA, Vinson DR, Chatterjee N. Dynamic modeling and control of cryogenic air separation plants. In: 2nd IFAC symposium DYCORD'89, Maastricht, The Netherlands; 1989. p. 267–3.

[110] Roffel B, Betlem BHL, De Ruijter JAF. First principles dynamic modeling and multivariable control of a cryogenic distillation process. Comput Chem Eng 2000;24:111–23.

[111] Mueller I, Kenig EY. Reactive distillation in a dividing wall column: rate-based modeling and simulation. Ind Eng Chem Res 2007;46:3709–19.

[112] Gary JH, Handwerk GE. Petroleum refining: technology and economics. 3rd ed. New York: Marcel Dekker Inc.; 1994.

[113] Lee JY, Kim YH, Hwang KS. Application of a fully thermally coupled distillation column for fractionation process in naphtha reforming plant. Chem Eng Process 2004;43:495–501.

[114] Houghton J. Global warming and climate change – a scientific update. Environ Protect Bull 2002;066:21–6.

[115] Gadalla MA, Olujic Z, Jansens PJ, Jobson M, Smith R. Reducing CO_2 emissions and energy consumption of heat-integrated distillation systems. Environ Sci Technol 2005;39:6860–70.

[116] EPA, Environmental Protection Agency; August 2002. <http://www.epa.gov/globalwarming/climate/index.html>.

[117] DTI, Department of Trade and Industry; August 2002. <http://www.dti.gov.uk/epa/bpmar2001.pdf>.

[118] EIA, Energy Information Administration; October 2002. <http://www.eia.doe.gov/oiaf/kyoto/kyotorpt.html>.

[119] Sittig M. Petroleum refining industry energy-saving and environmental control. NJ: Noyes Data Corporation; 1978.

[120] Harbert WD. Preflash saves energy in crude unit. Hydrocarb Process 1978;57:123–5.

[121] Rivero R, Anaya A. Exergy analysis of a distillation tower for crude oil fractionation, computer-aided energy systems analysis, In: Winter annual meeting of the ASME, Dallas, Texas, 25–30 November, vol. 21; 1990. p. 55–62.

[122] Delaby O, Smith R. Minimization of flue gas emissions. Trans IChemE 1995;73:21–32.

[123] Manninen J, Zhu XX. Optimal gas turbine integration to the process industries. Ind Eng Chem Res 1999;38:4317–29.

[124] Balat M, Balat H. Recent trends in global production and utilization of bio-ethanol fuel. Appl Energy 2009;86:2273–82.

[125] Fatih Demirbas M. Biorefineries for biofuel upgrading: a critical review. Appl Energy 2009;86:S151–61.

[126] Naito K, Nakaiwa M, Huang K, Endo A, Aso K, Nakanishi T, et al. Operation of a bench-scale ideal heat integrated distillation column (HIDiC): an experimental study. Comput Chem Eng 2000;24:495–9.

[127] Iwakabe K, Nakaiwa M, Huang K, Nakanishi T, Røsjorde A, Ohmori T, et al. Energy saving in multicomponent separation using an internally heat-integrated distillation column (HIDiC). Appl Therm Eng 2006;26:1362–8.

[128] Kano M, Fukushima T, Makita H, Hasebe S. Multiple steady-states in a heat integrated distillation column (HIDiC). J Chem Eng Jpn 2007;40:824–31.

[129] Olujic Z, Fakhri F, De Rijke A, De Graauw J, Jansens PJ. Internal heat integration – the key to an energy conserving distillation column. J Chem Technol Biotechnol 2003;78:241–8.

[130] Fischer M, Tonon L. VGPlus trays: improving the proven. Sulzer Tech Rev 2004;1:12–4.

[131] Douglas JM. Conceptual design of chemical processes. 1st ed. New York: McGraw-Hill; 1988.

[132] Zhu Y, Liu X. Dynamics and control of high purity heat integrated distillation columns. Ind Eng Chem Res 2005;44:8806–14.

[133] Huang K, Wang S-J, Iwakabe K, Shan L, Zhu Q. Temperature control of an ideal heat-integrated distillation column (HIDiC). Chem Eng Sci 2007;62:6486–91.

[134] Mejdell T, Skogestad S. Estimation of distillation compositions from multiple temperature measurements using partial-least-squares regression. Ind Eng Chem Res 1991;30:2543–55.

[135] Mejdell T, Skogestad S. Composition estimator in a pilot-plant distillation column using multiple temperatures. Ind Eng Chem Res 1991;30:2555–64.

[136] William MJ, Massimo CDi, Montague GA, Tham MT, Morris AJ. Artificial neural networks in process engineering. IEE Proc – D 1991;138:256–66.

[137] Jana AK, Samanta AN, Ganguly S. Nonlinear model-based control algorithm for a distillation column using software sensor. ISA Trans 2005;44:259–71.

[138] Quintero-Marmol E, Luyben WL, Georgakis C. Application of an extended Luenberger observer to the control of multicomponent batch distillation. Ind Eng Chem Res 1991;30:1870–80.

[139] Huang K, Nakaiwa M, Akiya T, Owa M, Aso K, Takamatsu T. Dynamics of ideal heat integrated distillation columns. J Chem Eng Jpn 1996;29:656–61.

[140] Nakaiwa M, Huang K, Naito K, Endo A, Owa M, Akiya T, et al. A new configuration of ideal heat integrated distillation columns (HIDiC). Comput Chem Eng 2000;24:239–45.

[141] Gadalla MA. Retrofit design of heat-integrated crude oil distillation systems. PhD Thesis, UMIST, Manchester, UK; 2003.