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Introducing Vapor Recompression Mechanism in Heat-Integrated Distillation Column: Impact of Internal Energy Driven Intermediate and Bottom Reboiler

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A novel combination of internally heat-integrated distillation column (HIDiC) and vapor recompression column (VRC) with intermediate reboiler (IR) is proposed. Supplying heat at the highest temperature point (i.e., column bottom) of the VRC scheme is not thermodynamically favorable and, therefore, we aim to install the IR for better distribution of heat along the column length, thereby reducing the compressor work. Introducing IR in the combined HIDiC-VRC system formulates an open-loop variable manipulation policy to evaluate the comparative impact of internal and external heat sources on bottom liquid reboiling. With internal energy driven bottom reboiler, we further investigate the hybrid HIDiC-VRCIR column with proposing the two modes of compressor arrangement, namely parallel and series. Finally, a multicomponent distillation system is exampled to show the promising potential of the proposed HIDiC-VRCIR configurations in improving the energetic and economic performance over the HIDiC-alone and HIDiC-VRC schemes with reference to a conventional standalone column. © 2014 American Institute of Chemical Engineers *AIChE J*, 61: 118–131, 2015
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Introduction

The greenhouse effect is a natural phenomenon that leads to keep the Earth's surface warm. Like a greenhouse window, the greenhouse gases allow sunlight to enter and then prevent heat from leaving the atmosphere.[1] It is unfortunate that rapidly growing energy demand has led to increase the concentration of greenhouse gases (e.g., H_2O vapor, CO_2, and CH_4), amplifying the natural greenhouse effect. In addition to growing environmental concerns, the rising costs of energy have stimulated intensive research in boosting the energy efficiency of chemical processes.

Distillation that is used for about 95% of all fluid separation processes is a major energy consumer in the chemical industries.[2] In fact, it is reported[3] that 60% of energy used by the chemical industries is for distillation alone and surprisingly, this unit accounts for an estimated 10% of the US industrial energy consumption.[4] Distillation is one of the natural candidates for thermal integration because of low thermodynamic efficiency (i.e., typically 5–20%), high energy consumption and its importance in product recovery and purification.

Among the various thermally integrated distillation technologies scrutinized so far seeking lower energy consumption and better profitability, the most popular ones include the divided wall column (DWC),[5–12] vapor recompression column (VRC),[3,13–16] and heat-integrated distillation column (HIDiC). After several decades of research and development, the DWC technology has been successfully commercialized.* Presently, more than 100 DWC units are reported in operation worldwide,[18] and the number continues to rise. Conversely, the externally heat-integrated VRC scheme is a proven technology used to enhance the energy efficiency of a distillation column and it is already implemented in industrial practice for the separation of close-boiling mixtures.

Internally, HIDiC has emerged as a promising alternative to the conventional distillation processes in reducing the energy consumption and cost. The concept of HIDiC column was first proposed by Haselden[19] in 1958 for a gas separation unit. Subsequently, the idea was systematized by Mah and coworkers[20,21] under the name of secondary reflux and vaporization. Again, the HIDiC technology has attracted the attention of Japanese researchers as there were two big worldwide energy crises in 1970s. Since then, the research has focused in developing a number of variants of the HIDiC system, particularly around the end of the 20th to the beginning of the 21st century.[22] An excellent overview of the HIDiC structures can be found in Nakaiwa et al.[23] and Jana,[4] and references therein. Recently, several research groups[24–34] are devoted in advancing the HIDiC technology. This relatively new HIDiC column has now entered the large-scale testing phase in Japan and in the Netherlands.[35]

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*Leading companies include Montz and BASF.[17]

Supplying heat at the highest temperature point (i.e., column bottom) of the VRC scheme is not thermodynamically favorable, particularly when the boiling point temperatures of the components to be separated are far apart. In this regard, some developments are made[13,16,32,36] and it is recommended to install the intermediate reboiler (IR)/heat exchanger (HE) in a VRC structure that mainly targets to distribute the heat along the column length, thereby reducing the compressor work.

In a previous study,[36] we have introduced a mechanism detailing the optimal use of IR(s) in the VRC. A number of variants of the VRC system coupled with IR is developed there. Furthermore, attempts are made to evaluate the benefit of using an internal heat source over the steam, an externally supplied utility, in bottom liquid reboiling. Among the various forms of vapor recompression, the multistage VRC with double IR has been identified as the best performer for the separation of a wide-boiling mixture.

In this contribution, we propose a hybrid configuration of a thermally integrated distillation column by introducing the VRC with intermediate reboiler (VRCIR) in the HIDiC configuration. Formulating an open-loop variable manipulation mechanism, attempts are made to assess whether bottom liquid reboiling is likely to be more thermodynamically and economically favorable by the use of internal heat source than that of externally supplied utility. Subsequently, two modes of compressor arrangement, parallel and series, are proposed for the HIDiC-VRCIR column having an internal heat driven bottom reboiler in evaluating the energetic and economic potential. Compared to the double-compressor-based HIDiC-VRC system reported in the work of Kiran et al.,[22] the proposed triple-compressor-based hybrid scheme additionally includes an IR and a third compressor that is either arranged in parallel or series with the second compressor within the framework of VRC mechanism. A multicomponent wide-boiling mixture separation is considered to illustrate all the variants of the proposed configuration and to show the gradual performance improvement using these two additional elements (i.e., IR and third compressor) one-by-one. Till date, no such hybrid heat-integrated structure is proposed and scrutinized with an example system.

Internally Heat-Integrated Distillation Column: A Classical Approach

Distillation can be thought of as a combined operation of heat pump and heat engine, where the former adds work to the reboiler and the later removes it from the condenser.[34] In a conventional distillation column (CDiC), the input work is larger than the output work and it makes the operation an irreversible one. The thermal degradation associated with the temperature difference between the reboiler and condenser is the principal reason for thermodynamic inefficiency of distillation. To improve this situation, it is essential to reduce the degree of irreversibility, which can be greatly done by utilizing the internal heat sources in a proper manner.

Over the past decades, many studies geared toward the development of heat integration techniques for distillation column have been presented in the literature. A large number of these studies covers the internally HIDiC that shows promising potential in boosting the thermodynamic efficiency.

The basic structure of HIDiC system is shown in Figure 1. Under this framework, the distillation tower is primarily divided into two diabatic sections with reference to the feed stage. Consequently, the stripping section accompanies the trim-reboiler at the bottom, whereas the rectifying section includes the overhead condenser-cum reflux accumulator. Vapor leaving the top of the stripping column is compressed isentropically, causing an increase in both pressure and temperature. The main purpose of compression in the Comp1 is to elevate the pressure of the rectifier to provide a driving force for heat transfer to the stripper that operates at a normal pressure as the CDiC. Moreover, a pressure reducing valve (TV1) is installed in between the two diabatic sections for pressure adjustment.

As shown, the internal vapor streams of high pressure (HP) rectifying section are thermally coupled with the tray liquids of low pressure (LP) stripping section by the employment of a set of vertically placed internal HEs. This thermal arrangement leads to provide an additional liquid flow for the former section and vapor flow for the later one, thereby offering to reduce the utility consumption.

Introducing VRC in HIDiC Column: An Intensified Approach

Because the rectifying column operates at a higher pressure than the stripper, there arises a possibility of further intensification by thermally integrating the overhead vapor of rectifier with the bottom liquid of stripper in a HE (i.e., bottom reboiler). Primary objective of this hot (HP) and cold (LP) stream pairing is to recover the latent heat of top vapor, an internal heat source, and utilize it in liquid reboiling so that this intensified HIDiC column can further improve the thermodynamic efficiency over the HIDiC-alone scheme.[22,30,32] Achieving this goal may require the installation of a second compressor (Comp2) and this structure, as shown in Figure 2, gives rise to the HIDiC column operated in conjunction with a vapor recompression system. This novel combination of internal (HIDiC) and external (VRC) thermal integrations has the potential to reduce not only the steam consumption but also the cold utility requirement.

At this moment, it is important to highlight that instead of using a second compressor (Comp2) in the HIDiC-VRC column, alternatively the first compressor (Comp1) can be operated at a reasonably large compression ratio (CR) so that the criterion[†] concerning the requirement of thermal driving force for overhead vapor condensation in the bottom reboiler is satisfied. Interestingly, this issue is addressed earlier[22] showing that the use of two compressors, one for each HIDiC and VRC, in the HIDiC-VRC scheme is attractive in the aspect of both energy efficiency and cost than the use of a single compressor. Therefore, in the present study, we select the intensified HIDiC-VRC structure having double compressors for further advancement.

It is obvious that compared to the CDiC scheme, the HIDiC-alone additionally includes a compressor (Comp1). The intensified HIDiC-VRC configuration further involves a second compressor (Comp2), along with Comp1. Based on the qualitative analysis, therefore, it is indeed difficult to confirm if any advantage is offered by a heat integration system over a conventional standalone column. Hence, we believe that further analysis is warranted. Accordingly, we carry out a quantitative analysis in terms of both energy

[†]Throughout this study, we assume a minimum temperature difference ($\Delta T_{\min}$) of 20 K required for condensation of compressed vapor in thermal coupling.[37]

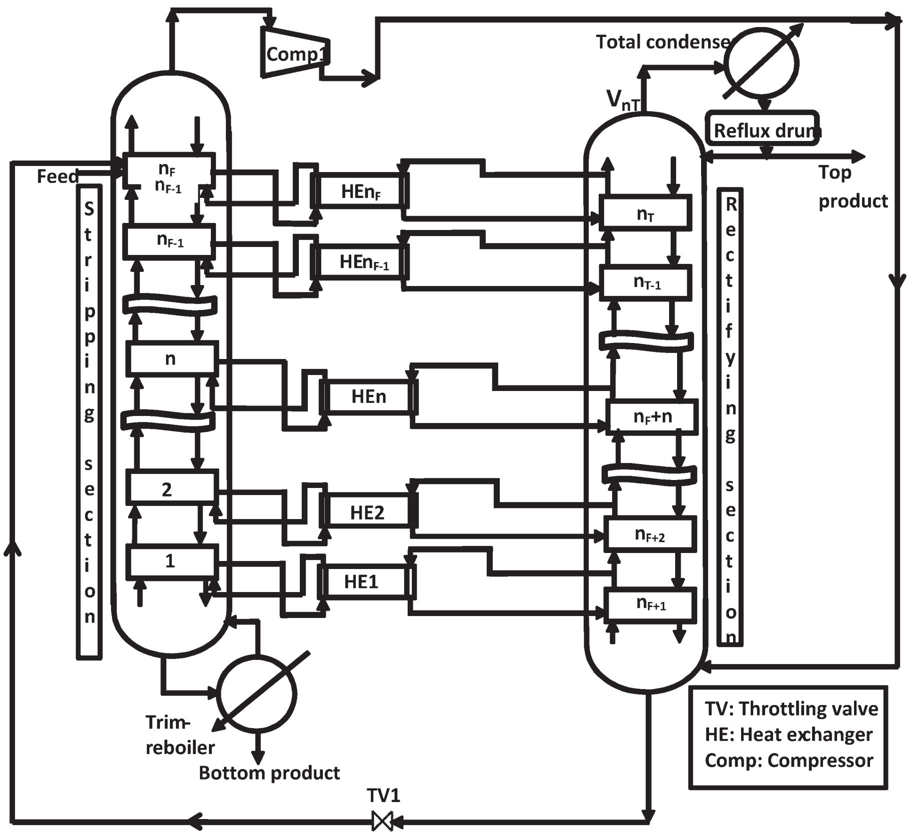

Figure 1. Schematic representation of an internally heat-integrated distillation column (HIDiC-alone).

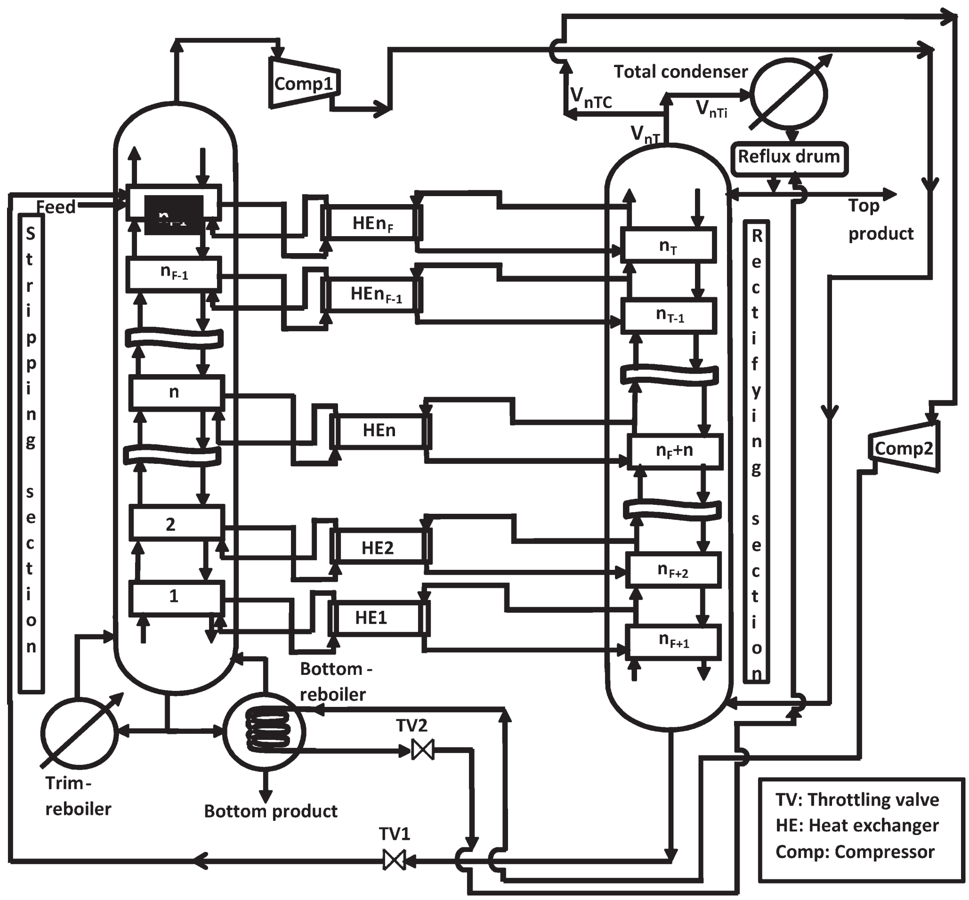

Figure 2. Schematic representation of an intensified HIDiC-VRC column.

Table 1. Cost Estimating Formula and Parameter Value[37]

■ Column shell: $\left(\frac{M\&S}{280}\right)$ $101.9D_c^{1.066}L_c^{0.802}(c_{in}+c_mc_p)$
Where, D_c is the column diameter, L_c the column height, $M\&S=$ 1625.9, and the coefficients $c_{in}=2.18$, $c_m=3.67$, and $c_p=1.2$.
■ Column tray: $\left(\frac{M\&S}{280}\right)4.7D_c^{1.55}L_c(c_s+c_t+c_m)$
Where, the coefficients $c_s=1$, $c_t=0$, and $c_m=1.7$.
■ Heat exchanger: $\left(\frac{M\&S}{280}\right)101.3A^{0.65}(c_{in}+c_m(c_t+c_p))$
Where, the coefficients $c_{in}=2.29$, $c_m=3.75$, $c_t=0.1$, and $c_p=1.35$.
■ Compressor: $\left(\frac{M\&S}{280}\right)517.5\mathrm{BHP}^{0.82}(c_{in}+c_t)$
Where, the coefficient $c_{in}=2.11$ and $c_t=1.0$.

consumption and total annualized cost (TAC). The formulation for estimating these two performance indexes is presented in Appendix A. Additionally, Table 1 reports the cost estimating formulas with relevant parameter values.

Hybrid HIDiC-VRC with IR: The Proposed Scheme

The use of IR in addition to the conventionally used trim-reboiler, both of which are driven by externally supplied heat (e.g., steam), in distillation operations gives an added advantage in terms of utility consumption and cost, particularly for the separation of large boiling range mixtures.[38] In the similar way, it is true to say that instead of supplying heat at the highest temperature point (i.e., column bottom) of a VRC scheme, it can be distributed along the column length by the installation of IR, thereby reducing the compressor load. The use of IR in VRC column is proposed a long back by Flower and Jackson.[13] In recent times, this concept is reintroduced and subsequently the VRCIR column is evaluated with the separation of a few systems, including the reactive ones.[16,36]

It is a fact that the compressor needs to operate at largest CR when the latent heat of overhead vapor is targeted to extract in bottom reboiler which operates at highest temperature. In the similar fashion, the compressor work starts decreasing as the location of reboiler moves toward the top of the column. This is the key motivation behind the use of an IR in the VRC column. At the same time, however, we should remember that shifting an IR upward may result in

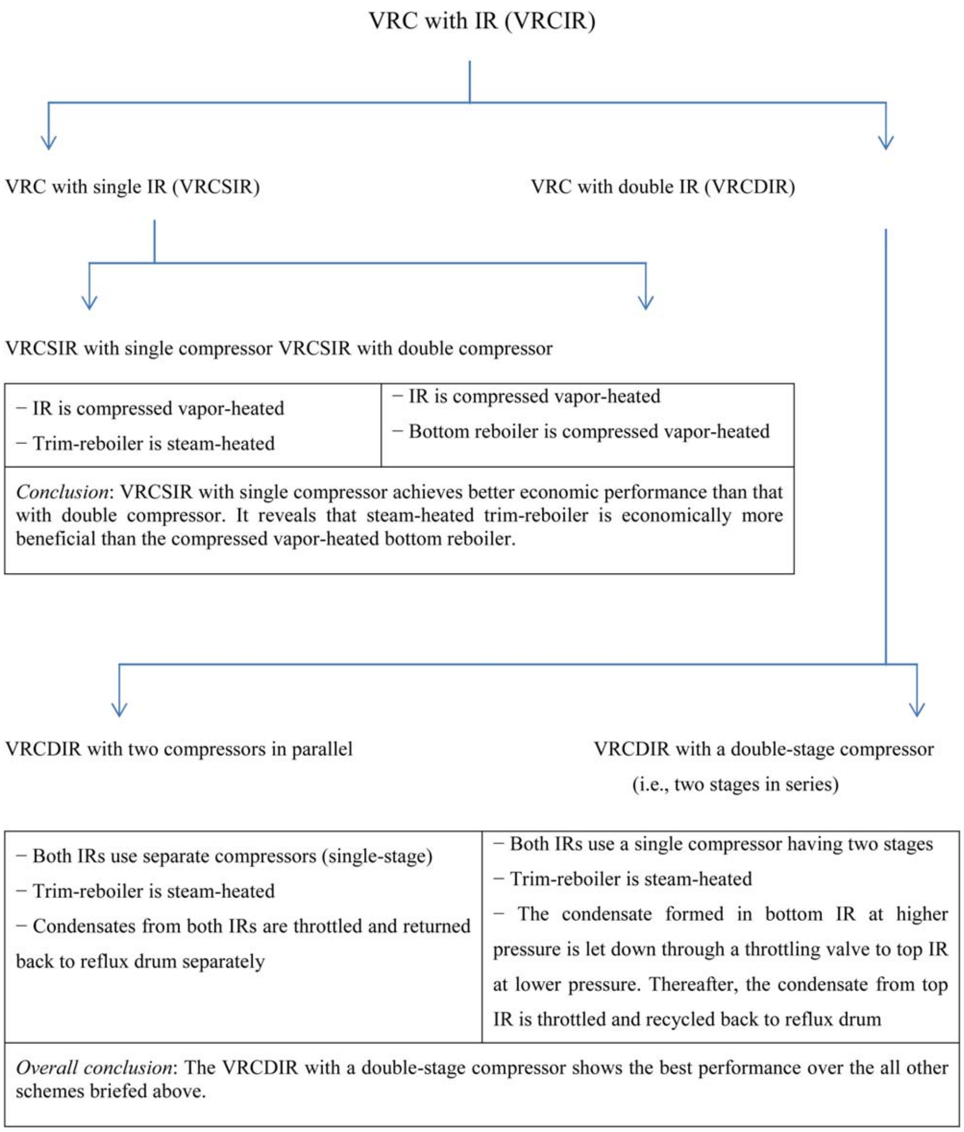

Figure 3. A comparative performance between several variants of VRCIR for the separation of a particular wide-boiling multicomponent reactive mixture.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

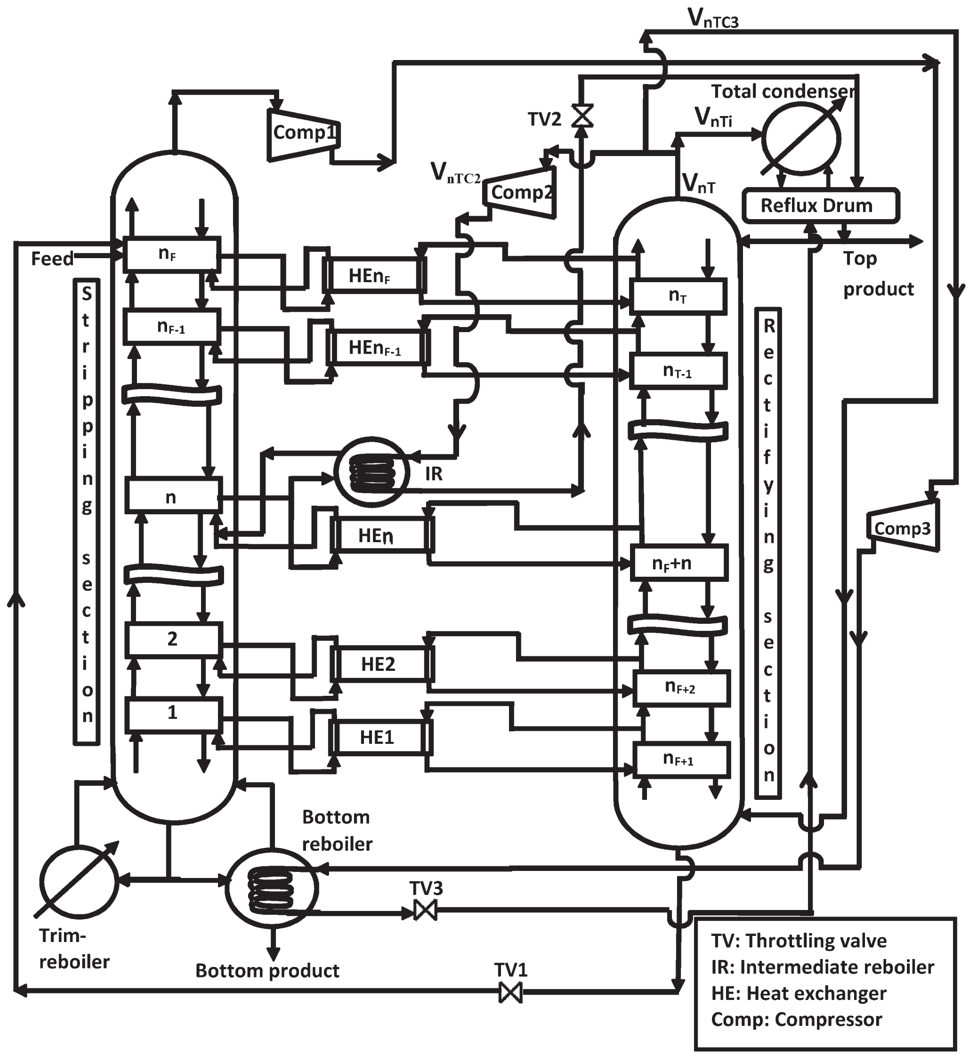

Figure 4. Schematic representation of the HIDiC-VRCIR with compressors in parallel.

the followings: the requirement of increased external hot utility at the bottom, and the participation of reduced amount of overhead vapor as a heat source in the IR, indicating an increase of coolant demand. This clearly indicates the necessity of finding a suitable position for IR with reference to some performance indexes.

One of our previous studies[36] has proposed a policy for the optimal use of IR(s) in the VRC. Several variants of the VRC scheme accompanying with IR are configured. Moreover, the use of an internal heat source (i.e., latent heat of overhead vapor) in bottom liquid reboiling is evaluated over the use of steam, an externally supplied utility. Figure 3 highlights all these schemes and their comparative performances. Among, the multistage VRC with double IR has been identified as the best performer for the separation of a specific mixture having widely different component boiling points.

In this work, we propose a novel scheme that combines the HIDiC column and VRC with IR. This hybrid HIDiC-VRCIR system is configured with an internal heat driven bottom reboiler in addition to a trim-reboiler. It is interesting to note that involving no trim-reboiler in a heat-integrated scheme is commonly known as an ideal configuration. The hybrid system in conjunction with the bottom reboiler is further proposed with two variants: HIDiC-VRCIR with compressors in parallel and HIDiC-VRCIR with compressors in series (i.e., HIDiC-VRCIR with a multistage compressor). In the following, these schemes are briefly presented.

HIDiC-VRCIR with compressors in parallel

As shown in Figure 4, the proposed HIDiC-VRCIR uses a single IR and a bottom reboiler, both of which receive energy from compressed vapor through condensation. For this arrangement, two compressors, namely Comp2 for IR and Comp3 for bottom reboiler, are installed in parallel. It might be possible to achieve better thermodynamic performance from a heat-integrated structure by the use of multiple IRs but at the expense of an enhanced complexity. Therefore, here we are strict to develop the hybrid HIDiC-VRCIR scheme accompanied with a single IR and an internal heat driven bottom reboiler. However, one can use more than one IR with extending the proposed methodology. Now, the two crucial issues, concerning the selection of tray-to-IR pairing and percent tray liquid that is to be vaporized in the IR, are addressed later with an example system.

Based on the assumption that states the requirement of 20 K thermal driving force for condensation of the compressed vapor, finding of operating parameters of the compressors operated in parallel mode is quite straightforward. We compute the CR from

$$\mathrm{CR}=\frac{P_\mathrm{o}}{P_\mathrm{i}}=\left(\frac{T_\mathrm{o}}{T_\mathrm{i}}\right)^{\mu/(\mu-1)} \tag{1}$$

where, P and T designate the pressure and temperature, respectively, and subscripts i and o represent the input and output, respectively. The polytropic coefficient, μ ($=C_p/C_v$) can be calculated from

$$1/(\mu-1)=\sum[y_i/(\mu_i-1)] \tag{2}$$

In the above equation, C_p and C_v are heat capacities, and y_i the mole fraction of any vapor component i. Obviously, here $T_\mathrm{o}=T_\mathrm{s}+20$, where T_s represents the temperature of a stream coupled with the compressed vapor (at T_o) in IR/bottom reboiler.

The heat load of a CDiC column is estimated in terms of its reboiler duty (Q_R). Accordingly, the total heat consumed ($\bar{Q}_\mathrm{Cons}$) by the CDiC is obtained from

$$\bar{Q}_\mathrm{Cons}=Q_\mathrm{R}\times t_\mathrm{o} \tag{3}$$

where, t_o is the total operational time. Obviously, there is no need to multiply Q_R with t_o if one wishes to have $\bar{Q}_\mathrm{Cons}$ in terms of heat consumption rate. It should be pointed out that here, we target to consume the same amount of heat ($\bar{Q}_\mathrm{Cons}$) in all distillation configurations, including the heat integrated ones. With this constraint, one may achieve the same product quality and quantity from all columns that make sense for a meaningful comparison between them.

An Open-Loop Variable Manipulation Policy. In this hybrid HIDiC-VRCIR heat-integrated scheme, there are several heat duty terms and they are involved with: trim-reboiler (Q_e), bottom reboiler (Q_BR), intermediate reboiler (Q_IR), compressor (Q_Comp), and internal heat exchangers (HE) connected between rectifier and stripper in HIDiC (Q_HE). Aiming to run the hybrid configuration at a fixed heat duty of $\bar{Q}_\mathrm{Cons}$, we need to devise an operational policy that adjusts the manipulated variables in an open-loop fashion. For this, at first we should know whether the total heat available from internal sources ($=Q_\mathrm{BR}+Q_\mathrm{IR}+Q_\mathrm{HE}$) is more or less than $\bar{Q}_\mathrm{Cons}$. Accordingly, the variable manipulation policy is formulated considering the existence of two scenarios as detailed below.

Scenario 1: When $\bar{Q}_{Cons} > Q_{BR}+Q_{IR}+Q_{HE}$. In this case, the total heat required for a thermally coupled column is more than the available heat from all internal sources. It clearly indicates the requirement of a trim-reboiler that can supply the makeup heat from an external source (Q_e) as

$$Q_\mathrm{e}=\bar{Q}_\mathrm{Cons}-(Q_\mathrm{BR}+Q_\mathrm{IR}+Q_\mathrm{HE}) \tag{4}$$

Here, Q_e acts as a manipulated variable. Obviously, this scenario does not involve any overhead condenser because of the participation of entire top vapor from the rectifier in compression followed by condensation in bottom reboiler.

Scenario 2: When $\bar{Q}_{Cons} < Q_{BR}+Q_{IR}+Q_{HE}$. The heat integration system falls under Scenario 2 when the total heat provided by internal sources is more than sufficient in operating the HIDiC-VRCIR column at a desired state. In this situation, we have mainly two options left: either utilize the excess heat, amounting $(Q_\mathrm{BR}+Q_\mathrm{IR}+Q_\mathrm{HE})-\bar{Q}_\mathrm{Cons}$, in distillation operation or run the column supplying an exact amount of energy ($\bar{Q}_\mathrm{Cons}$) with the rejection of excess heat. In the former case, there is a chance of product degradation in terms of quality and/or productivity. This may happen mainly because of undesired reboiling of a heavier fraction by the excess heat, particularly when the column operates at an optimal heat duty, and this issue is not addressed in this study.

Here, we manipulate the overhead vapor (V_{n_T}) by splitting it into two streams: one part of V_{n_T}, namely $V_{n_\mathrm{T}C}$, is compressed and subsequently, it condenses in the bottom reboiler releasing latent heat (λ) to produce boil-up vapor. The remainder of V_{n_T}, namely $V_{n_\mathrm{T}i}$, is remained as an unused internal heat source and sent to an overhead condenser. It is worth noticing that the $V_{n_\mathrm{T}C}$ is adjusted in such a way that it can exactly supply the heat required for running the hybrid column (i.e., $\bar{Q}_\mathrm{Cons}-Q_\mathrm{HE}$) at a desired condition. Accordingly, we further split $V_{n_\mathrm{T}C}$ into two streams, namely $V_{n_\mathrm{T}C_2}$ and $V_{n_\mathrm{T}C_3}$. The former stream enters the second compressor (Comp2) that is connected with an IR and the later stream flows into Comp3 that is connected with the bottom reboiler. Now, we can compute these streams as follows

$$V_{n_\mathrm{T}C_2}=\frac{Q_\mathrm{IR}}{\lambda\ (\text{at } T_{n_\mathrm{T}C_2})} \tag{5a}$$

$$V_{n_\mathrm{T}C_3}=\frac{Q_\mathrm{BR}}{\lambda\ (\text{at } T_{n_\mathrm{T}C_3})} \tag{5b}$$

with

$$V_{n_\mathrm{T}C}=V_{n_\mathrm{T}C_2}+V_{n_\mathrm{T}C_3} \tag{5c}$$

Here, $T_{n_\mathrm{T}C}$ denotes the temperature of compressed overhead vapor. At this point, it should be noted that $\bar{Q}_\mathrm{Cons}$ is obtained from Eq. 3, while Q_HE is known from the HIDiC-alone scheme discussed earlier as well as in Appendix B (see Eqs. B5a and B5b). Now to determine Q_IR for Eq. 5a, we conduct a sensitivity test on the basis of TAC. Actually, in this test that is shown later with an example system, we calculate Q_IR with the selection of an amount of stripper tray liquid that must be allowed to enter the IR, ensuring an optimal TAC. Knowing $\bar{Q}_\mathrm{Cons}$, Q_HE, and Q_IR, we can easily calculate $Q_\mathrm{BR}(=\bar{Q}_\mathrm{Cons}-Q_\mathrm{HE}-Q_\mathrm{IR})$ for Eq. 5b.

Now, it is straightforward to compute $V_{n_\mathrm{T}i}$ with known $V_{n_\mathrm{T}C}$ as

$$V_{n_\mathrm{T}i}=V_{n_\mathrm{T}}-V_{n_\mathrm{T}C} \tag{6}$$

It is now obvious that Scenario 1 manipulates the external makeup heat (Q_e), involving a trim-reboiler but no condenser. Conversely, Scenario 2 requires an overhead condenser for the manipulation of top vapor rate and no trim-reboiler, and therefore, this scenario corresponds to an ideal configuration. It is worth noticing that the same variable manipulation mechanism can also be used for the HIDiC-VRC column (Figure 2) with the consideration of $Q_\mathrm{IR}=0$.

In this parallel mode of HIDiC-VRCIR operation, the condensates formed in IR and bottom reboiler are throttled separately in TV2 and TV3, respectively, and then they are sent back to the reflux accumulator. Aiming to make this scheme more realistic, necessary arrangement is made for the vapor

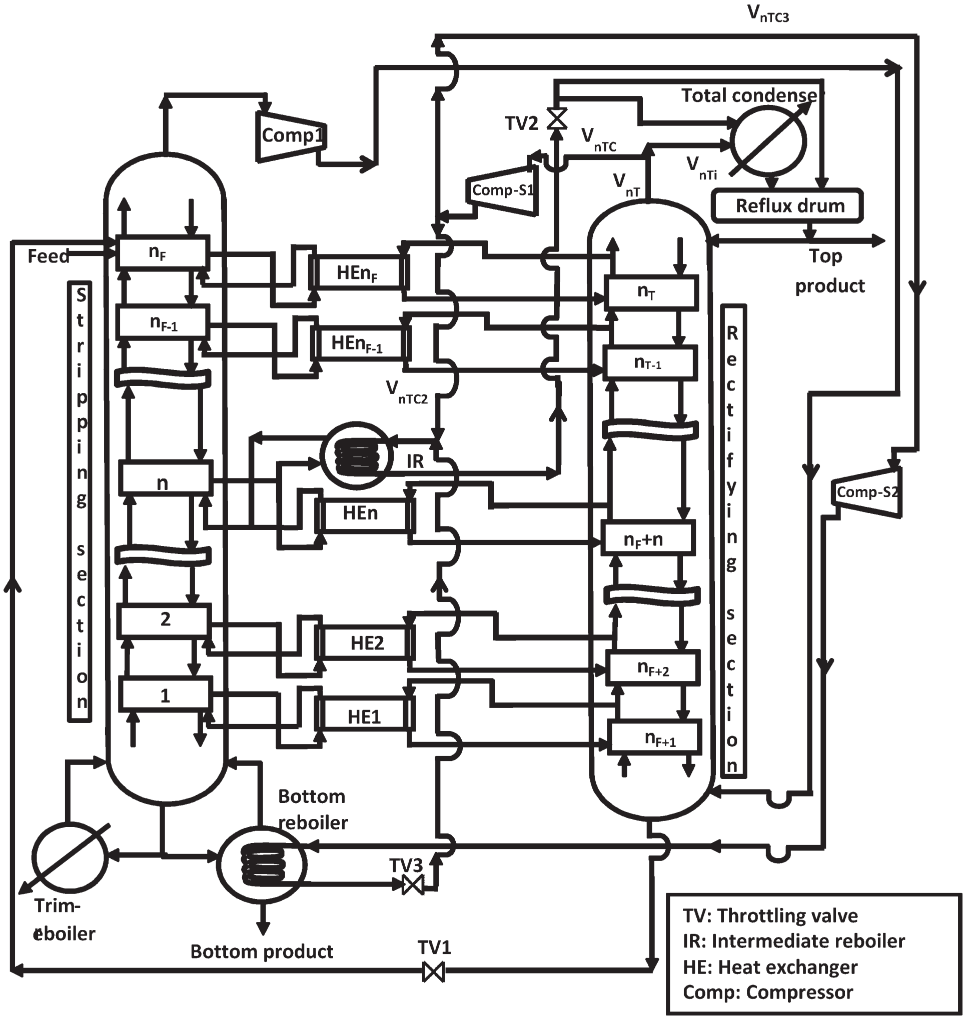

Figure 5. Schematic representation of the HIDiC-VRCIR with compressors in series.

fraction produced in throttling valves to flow into the overhead vapor line for condensation. Again, part of the accumulated liquid is refluxed back to the top stage of the column, and the remainder is drawn off as the distillate.

HIDiC-VRCIR with compressors in series

As shown the series mode of HIDiC-VRCIR column in Figure 5, a part or the whole of the overhead vapor leaving the rectifier is compressed in the first stage of a compressor (Comp-S1) to an appropriate pressure. Then, a fraction of this compressed vapor is thermally paired with tray liquid of the stripper in an IR. The condensate formed in the IR is subsequently depressurized by the use of a throttling valve (TV2), yielding a liquid–vapor mixture. The liquid fraction is returned back to the reflux drum and the vapor fraction to the overhead vapor line. Remaining portion of the vapor stream leaving Comp-S1 is further pressurized in the second stage (Comp-S2) of a multistage compressor before utilizing it as a heat source in the bottom reboiler. The condensate leaving the bottom reboiler at higher pressure is let down through TV3 to IR at relatively LP thus recovering work at the same time. This way the multistage compressor in series mode works in the hybrid HIDiC-VRCIR scheme.

To meet the criterion concerning the distillation operation at a fixed heat duty, we follow the same open-loop variable manipulation policy developed earlier. In Scenario 1, first the entire top vapor is compressed in Comp-S1 and then, a fraction of it is used in IR and the rest is further subjected to compression in Comp-S2 before utilizing its latent heat in the bottom reboiler. Like the parallel mode of HIDiC-VRCIR operation, the series arrangement under Scenario 1 involves a trim-reboiler but no overhead condenser because of the reason stated earlier. As far as Scenario 2 is concerned, the hybrid scheme manipulates the overhead vapor splitting so that the column operates at a prespecified heat load with rejecting the excess heat to a coolant stream in the overhead condenser. As a consequence, Scenario 2 that corresponds to an ideal heat-integrated configuration avoids the employment of a trim-reboiler. Note that the both scenarios ensure the following condition

$$\bar{Q}_{\rm Cons}=Q_{\rm BR}+Q_{\rm IR}+Q_{\rm HE}+Q_{\rm e} \tag{7}$$

with $Q_{\rm e}=0$ for Scenario 2.

An Illustrative Example: Separation of a Multicomponent Hydrocarbon System

To evaluate the quantitative performance of all variants of the proposed heat-integrated configuration, we simulate a multicomponent distillation column that is referred to as the

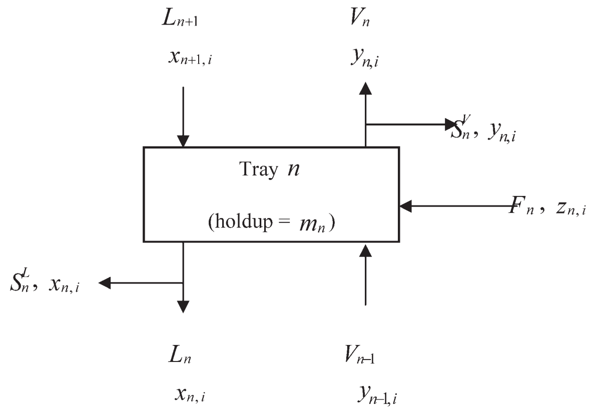

Figure 6. Quantities associated with a typical *n*th tray.

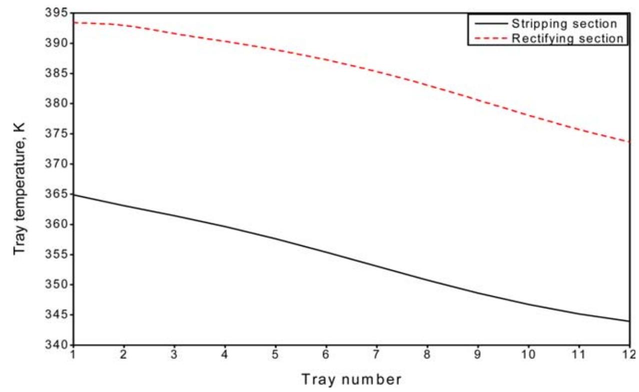

Figure 7. Steady-state tray temperature profile (in this figure, stage numbering in both the sections has started from bottom up).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

CDiC. The CDiC serves as a basis for comparing all thermally coupled structures. The representative column separates a ternary hydrocarbon mixture containing *n*-butane (*n*-C_4), *n*-pentane (*n*-C_5), and *n*-hexane (*n*-C_6), which have widely different boiling points. The column has total 24 trays, excluding the reboiler and condenser, and trays are counted from bottom up. It operates at a bottom pressure of 409.12 kPa with a stage pressure drop of 0.3 kPa.

For a typical *n*th tray shown in Figure 6, the modeling equations are derived in Appendix B. Obviously, the model comprises of the ordinary differential equations (ODEs) and the algebraic equations (AEs). The former equations are obtained by the application of the conservation principle and the later ones represent the physical properties, vapor–liquid equilibrium, and so forth, all of which provide support for solving the ODEs.

The coupled modeling equations are simulated in MATLAB environment. Details of computer simulation and concerned algorithm are given elsewhere.[39] The column specifications and operating conditions are documented in Table 2.

Table 2. Process Parameters and Steady State Values

Items	CDiC	HIDiC-VRCIR
Feed flow rate (kmol/s)	0.02	0.02
Feed composition (*n*-C_4/*n*-C_5/*n*-C_6)	0.3/0.4/0.3	0.3/0.4/0.3
Top composition (mol fract)	0.993/0.007/0.00	0.9933/0.0067/0.00
Bottom composition (mol fract)	0.0103/0.5643/ 0.4254	0.0114/0.5956/ 0.393
Distillate (top) temperature (K)	315.59	370.19 (rectifier)
Bottoms temperature (K)	368.05	367.79 (stripper)
Distillate rate (kmol/s)	0.0059	0.0060
Bottoms rate (kmol/s)	0.0141	0.0140
Reflux ratio	2.03	1.60
Reboiler duty (kW)	440.50	0.00[a]
Tray efficiency (%)	70	70
Total number of trays (excluding total condenser and reboiler)	24	12 + 12
Feed stage	12	12
Stage pressure drop (kPa)	0.3	0.3
Bottom stage pressure (kPa)	409.12	409.12 (stripper)

[a]The HIDiC-VRCIR is an ideal configuration.

HIDiC-alone scheme: Development and simulation results

At the first stage of configuring a HIDiC column, we divide the tray tower into two diabatic sections, having the same number of trays (= 12) in both of them. As stated, the stripper accompanies a trim-reboiler at the bottom and the rectifier includes a trim-condenser at the top. An isentropic compressor is placed in between the rectifier and stripper, and this leads to run the former column at higher pressure than the later one. To depressurize the rectifier bottom stream before its entry at the top of stripper, a reducing valve is also installed.

The modeling equations, which represent the heat integration arrangement of the HIDiC column, are documented in Appendix B. Now, for identifying the tray-to-tray pairs for heat exchange between two diabatic sections, we produce a temperature profile in Figure 7 for both of them along their length. Fixing a cutoff value for thermal driving force at

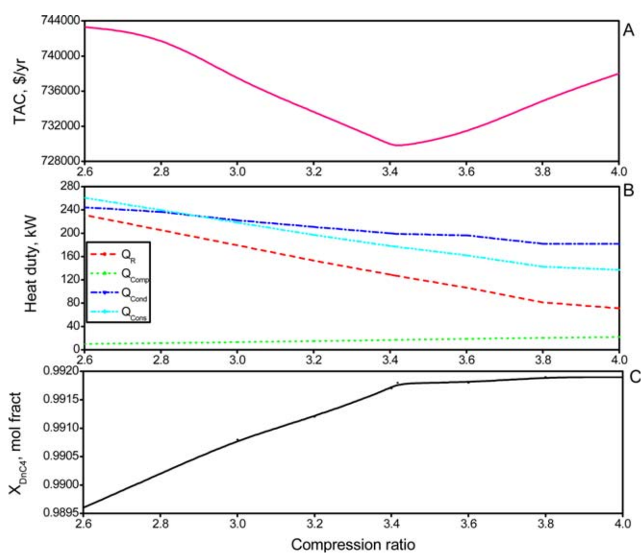

Figure 8. Effect of CR on (A) TAC, (B) energy consumption, and (C) distillate purity of the HIDiC-alone column.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

20 K, the comparative temperature plot indicates the possibility of thermal coupling for all 12 trays between the two columns. Accordingly, the 12 internal HEs are proposed to equip with the following pairs (stripper tray-rectifier tray): 1–13, 2–14, 3–15, 4–16, 5–17, 6–18, 7–19, 8–20, 9–21, 10–22, 11–23, and 12–24.

For a heat-integrated system, usually we chose the values for five parameters: the total number of stages (n_T), the stage pressure drop (ΔP), the reflux ratio (RR), the product of the overall heat-transfer coefficient and the heat exchange area (UA), and the CR. Among them, the first three are specific to both the HIDiC and its conventional counterpart (i.e., CDiC). Actually, in the CDiC model, the CR and UA are not involved as there is no existence of compressor and internal HE connected between two stages.

It is a fact that by decreasing the total number of stages in a thermally coupled configuration, one may achieve better energy efficiency performance with an improvement in economic potential. This is mainly because of the reduction in compressor work. But at the same time, the product quality has to be compromised. Therefore, in the present study, the total number of stages is kept same (= 24) for both the conventional and heat-integrated column.

The values of other four variables, namely CR, UA, ΔP, and RR, are selected by performing several sensitivity tests. As indicated above, the parameter values are chosen here such that they can provide a minimum TAC in addition to desired product specification. As shown in Figure 8, aiming to find the optimal CR, it is varied from 2.6 to 4 with fixing the UA, ΔP, and RR values at 0.8 kW/K, 0.3 kPa, and 1.8, respectively. Obviously, the CR of about 3.42 shows the best performance in terms of TAC and interestingly, this CR leads to achieve the distillate purity of n-C_4 close to that obtained for CDiC at steady-state condition. For brevity, other sensitivity tests are not detailed and the values for rest three parameters are finally selected as: RR = 1.6, $UA = 0.8$ kW/K, and $\Delta P = 0.3$ kPa.

The overall energy consumed by the representative CDiC and the HIDiC-alone scheme are computed as 440.5 and 176.79 kW, respectively. This represents an energy savings of 59.87% achieved by the HIDiC-alone. Moreover, the heat integration provides a 55.58% savings in operating cost, showing a substantial improvement in both utility consumption and cost. Although it is well known that the improved thermodynamic performance is usually achieved at the cost of an increased capital investment, this is not evident in Table 3 for HIDiC-alone column. In addition to a reduction of energy consumption by 59.87%, the thermal integration secures a 3.68% savings in TAC as well, yielding a payback period of 2.57 years (4.34 years with considering 20% penalty[‡]).

HIDiC-VRC scheme: Development and simulation results

As detailed earlier, the coupling of HIDiC with VRC scheme leads to provide an additional source of energy (i.e., latent heat) associated with the hot overhead vapor for reboiling the relatively cold bottom liquid, thereby reducing the consumption of both hot and cold utilities. As the thermal driving force existed between the rectifier top vapor and stripper bottom liquid (= 2.4 K) is less than 20 K that is the least requirement ($\Delta T_{\min}$) for phase change, we use a second compressor, Comp2 (see Figure 2). Now using Eq. 1 with $\Delta T_{\min} = 20$ K, we obtain the CR of 1.24 for Comp2. Operating Comp2 with this typical CR, we observe that the latent heat released by the entire overhead vapor in bottom reboiler (Q_{BR}) is larger than the energy demand [$=\bar{Q}_{\text{Cons}} - Q_{\text{HE}} =$ (440.5 − 313.66) kW = 126.84 kW]. It reveals that $\bar{Q}_{\text{Cons}} < Q_{BR} + Q_{HE}$, indicating the existence of Scenario 2. Implementing the variable manipulation mechanism formulated in HIDiC-VRCIR with compressors in parallel Subsection, we split the overhead vapor to adjust the vapor inflow rate to the compressor so that it can provide no excess heat to the reboiler content. As there is no requirement of external heat source in bottom liquid reboiling of the sample system, it is appropriate to call this structure as the ideal HIDiC-VRC scheme.

It is evident in Table 3 that this ideal configuration shows a significant savings in both energy consumption (= 82.72%) and utility cost (= 75.91%). In fact, in comparison with the HIDiC-alone, the HIDiC-VRC column secures about a 23 and 20% increment, respectively. Over a payback period of 3 years, this combined structure also improves the TAC savings to more than 9%.

Proposed HIDiC-VRCIR scheme: Development and simulation results

HIDiC-VRCIR with Compressors in Parallel. Now, we would like to introduce an IR in the ideal HIDiC-VRC column that is developed above. At this moment, it should be pointed out that this hybrid HIDiC-VRCIR does not require any external heat driven trim-reboiler and it includes three compressors. As shown in Figure 4, one compressor (Comp1) is associated with the HIDiC column, second one (Comp2) is for IR, and third one (Comp3) for bottom reboiler.

Prior to analyzing the performance of the parallel mode of HIDiC-VRCIR column, it is required to find the amount of stripper tray liquid to be allowed to IR for vaporization and to fix the IR-stripping tray pairing. For this purpose, we perform sensitivity tests with considering the TAC and energy savings as the two determining factors. It is evident from Figure 9 that about 33 mol % of tray liquid of the stripper leads to achieve the minimum TAC and maximum energy savings. By performing a similar test to choose the IR-stripping tray pairing (not shown for brevity), we finally adopt a tray liquid of about 33 mol % that is allowed to IR from sixth tray for vaporization.

As indicated earlier, like the HIDiC-VRC column, this hybrid scheme falls under Scenario 2. Hence, the parallel mode of HIDiC-VRCIR configuration manipulates the vapor inflow rate to both of the compressors (Comp2 and Comp3). The fraction of top vapor that flows to Comp2 is calculated from Eq. 5a as

$$V_{n_T C_2} = \frac{0.33 \dot{m}_6 \ \lambda \ (\text{at } T_6)}{\lambda \ (\text{at } T_{n_T C_2})} \tag{8}$$

with

$$Q_{IR} = 0.33 \dot{m}_6 \lambda \ (\text{at } T_6) \tag{9}$$

Here, m_6 and T_6 are the liquid holdup and tray temperature, respectively, with respect to sixth tray. Similarly, the vapor inflow rate to Comp3 is determined using Eq. 5b.

[‡]It is reasonable to give extra penalties to the cost estimation because the installation of internal heat transfer area into the HIDiC is much more complex than that for CDiC.

Table 3. Comparative Quantitative Performance Between the Proposed Schemes with Reference to the CDiC Column

Item	CDiC	HIDiC-Alone	HIDiC-VRC	HIDiC-VRCIR[a]	HITDiC-VRCIR[b]	
					Series	Parallel
Operating cost ($/yr)						
Condenser						
Duty (kW)	411.40	198.70	130.81	51.42	23.37	24.68
CW required (ton/yr)	2,808,007.67	1,372,180.05	892,840.0	351,000	159,510	168,451
Cost of CW	168,480.46	82,330.80	53,000.27	21,060.00	9570.60	10,107.10
Trim-reboiler (steam-heated)						
Duty (kW)	440.5	126.84	0.0	27.46	0.0	0.0
Steam required (ton/yr)	9326.27	2701.04	0.0	584.35	0.0	0.0
Cost of steam	182,608.40	52,886.42	0.0	11,441.62	0.0	0.0
Intermediate reboiler (compressed vapor-heated)						
Duty (kW)	–	–	–	97.75	97.75	97.75
Cost	0.0	0.0	0.0	0.0	0.0	0.0
Bottom reboiler (compressed vapor-heated)						
Duty (kW)	–	–	126.84	–	27.46	27.46
Cost	0.0	0.0	0.0	0.0	0.0	0.0
Comp1						
Duty (kW)	0.0	16.65	16.65	21.30	21.30	21.30
Cost of electricity	0.0	20,715.98	20,715.98	26,508.65	26,508.65	26,508.65
Comp2						
Duty (kW)	0.0	0.0	8.72	2.826	3.09	2.825
Cost of electricity	0.0	0.0	10,851.55	3516.30	3846.80	3515.90
Comp3						
Duty (kW)	0.0	0.0	0.0	0.0	0.0878	0.344
Cost of electricity	0.0	0.0	0.0	0.0	109.20	428.02
Energy saving (%)	–	59.87	82.72	77.33	83.33	83.33
Total utility cost ($/yr)	351,088.86	155,933.20	84,567.80	62,526.57	40,035.25	40,559.67
Utility cost savings (%)	–	55.58	75.91	82.19	88.60	88.45
Capital Cost ($)						
Condenser	111,618.03	70,079.78	53,000.27	28,888.07	17,301.60	17,524.67
Trim-reboiler	142,409.29	63,440.50	0.0	23,467.30	0.0	0.0
Internal heat exchangers	0.0	492,194.84	492,194.84	493,387.93	493,358.64	493,358.62
Intermediate reboiler	0.0	0.0	0.0	80,591.40	80,591.40	80,591.40
Bottom reboiler	0.0	0.0	95,462.32	0.0	35,334.26	35,334.26
Column	347,376.05	347,376.05	347,376.05	347,376.05	347,376.05	347,376.05
Trays	617,728.32	617,728.32	617,728.32	617,728.32	617,728.32	617,728.32
Comp1	0.0	130,150.00	130,150.00	159,320.00	159,311.04	159,311.04
Comp2	0.0	0.0	76,591.94	30,399.00	32,723.55	30,397.11
Comp3	0.0	0.0	0.0	0.0	1763.73	5406.07
Total capital cost ($)	1,219,131.69	1,720,969.49	1,812,503.74	1,781,158.07	1,785,488.59	1,787,027.54
TAC ($\theta = 3$) ($/yr)	757,466.09	729,589.70	688,735.71	656,245.93	635,198.11	636,235.52
TAC savings (%)	–	3.68	9.07	13.36	16.14	16.00
Payback period (yr)	–	2.57	2.23	1.95	1.82	1.83
Payback period (with a penalty of 20% added to the total capital cost) (yr)	–	4.34	3.59	3.18	2.97	3.00

[a]Without bottom reboiler.
[b]With bottom reboiler.

With this manipulation policy, applying Eq. 1, we obtain the CR for Comp2 and Comp3 that are arranged in parallel as 1.164 and 1.216, respectively. Actually the source (i.e., overhead vapor) is made hotter than the sink (i.e., reboiler and IR contents) by compression action. In the next, we conduct a quantitative performance analysis for comparison. In Table 3, one may readily find that the parallel mode of ideal HIDiC-VRCIR saves 83.33, 88.45, and 16% in energy consumption, operating cost, and TAC, respectively. This improvement leads to a reasonably low payback period of 1.83 years (3 years with a 20% extra penalty to CI). Clearly, this hybrid HIDiC-VRCIR outperforms the HIDiC-VRC and HIDiC-alone schemes.

HIDiC-VRCIR with Compressors in Series. Only difference made in series mode of ideal HIDiC-VRCIR operation over its parallel counterpart is the compressor arrangement. The position of IR and the amount of stripper tray liquid fed to the IR are remained identical in both of them. This series mode of HIDiC-VRCIR column is detailed earlier, and its CRs for Stage 1 and Stage 2 are determined as 1.164 and 1.045, respectively. Implementing the variable manipulation algorithm under Scenario 2, we further proceed to quantify the energetic and economic potential. It is evident from Table 3 that this series mode of HIDiC-VRCIR column shows more or less same results compared to the parallel mode, but better performance over the HIDiC-VRC and much better than the HIDiC-alone scheme with reference to the CDiC column.

Now, we wish to analyze this series mode of hybrid HIDiC-VRCIR with respect to the VRCIR-alone reported in Kumar et al.,[36] which shows that the series (i.e., multistage compressor) arrangement secures better energy savings and economic performance over the parallel arrangement for the separation of a mixture having widely different boiling point.

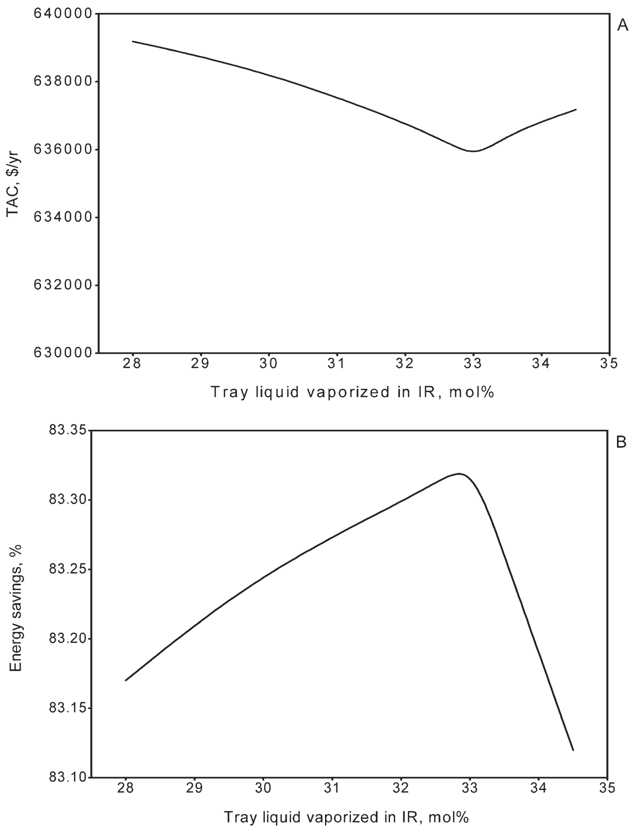

Figure 9. Effect of stripper tray liquid vaporized in the IR on (A) TAC and (B) energy savings.

For the VRCIR-alone configuration, this happens mainly because of the availability of latent heat of a large vapor fraction of bottom reboiler condensate after pressure adjustment in reboiling the relatively low temperature IR content, thereby reducing both the compressor work and cold utility requirement.

Conversely, although a wide boiling mixture is similarly treated in the present work, the situation existed in the HIDiC-VRCIR column is somewhat different. Actually, in this hybrid scheme, unlike the VRCIR-alone, the temperature difference between the source (rectifier top) and sink (stripper bottom) is relatively much small and positive because of the operation of rectifier at an elevated pressure, leading to the separation of a close-boiling-like mixture. As a consequence, TV3 produces a negligibly small quantity of vapor, which offers a marginal advantage in terms of latent heat supply to the IR as well as reduced coolant consumption. Hence, as shown in Table 3, almost no performance improvement is achieved by the series mode over the parallel mode of ideal HIDiC-VRCIR column.

Comparison of HIDiC-VRCIR Schemes: Bottom Reboiler vs. Trim-Reboiler. The ideal HIDiC-VRCIR scheme is tested and compared above between its series and parallel arrangements. Note that both the arrangements use the internal heat driven bottom reboiler, not the trim-reboiler that is operated with externally supplied heat. Now, we are interested to explore the suitability of a reboiler, among these two, for the HIDiC-VRCIR scheme. Accordingly, we replace the bottom reboiler by the steam driven trim-reboiler in the said scheme and perform a comparative study for the same example mixture.

As shown earlier, the sample large boiling range mixture gets separated as a close-boiling mixture in the hybrid column. Therefore, it is unlikely that there would be any significant change in economic performance by the replacement of internal heat by an external steam in vaporizing the reboiler content. In fact, comparing the performance of HIDiC-VRCIR having a trim-reboiler with any one of the ideal HIDiC-VRCIRs in Table 3, one may readily find that the ideal configuration shows better savings in the aspects of both utility consumption and TAC. It clearly contradicts the results shown in the case of VRCIR-alone[16,36] and the reason for this is indicated earlier with regard to the thermal driving force. Now, it can be concluded that there must be an optimal temperature difference (ΔT) between the sink and source for a particular mixture, above which the use of trim-reboiler is economically beneficial and below that the employment of bottom reboiler would make the operation more cost effective.

It is now suggested to determine the optimal temperature difference based on an economic parameter, namely TAC. For a heat-integrated configuration, the optimal value is system specific and it should provide the same economic performance whether one uses trim-reboiler or bottom reboiler.

Conclusions

In this article, a novel combination of HIDiC and VRC with an IR is proposed. A process configuration is developed aiming to thermally couple the tray liquid of a LP stripper with the overhead vapor leaving the HP rectifier in an IR. By this way, the compressor work gets reduced in the proposed HIDiC-VRCIR column compared to the HIDiC-VRC scheme. It is investigated for a hydrocarbon system having components with widely different boiling points that the use of an IR in the HIDiC-VRCIR column equipped with an externally supplied steam driven trim-reboiler secures an improvement in energy savings and cost compared to the HIDiC-VRC and HIDiC-alone with reference to a conventional standalone column.

Formulating an open-loop variable manipulation algorithm for an optimal use of internal heat sources, we evaluate the comparative impact of internal and external heat sources on bottom liquid reboiling. In this hybrid HIDiC-VRCIR scheme, unlike the VRCIR-alone, the temperature difference between the source (rectifier top) and sink (stripper bottom) is relatively much small and it is, in fact, positive for the sample wide-boiling mixture because of the operation of rectifier at an elevated pressure, leading to the separation of a close-boiling-like mixture. As a consequence, it is observed that the internal heat driven bottom reboiler provides better energy savings and economic performance over the steam-driven trim-reboiler in the hybrid column. In this light, it can be concluded that there must be an optimal temperature difference (ΔT) between the sink and source for a particular mixture, above which the use of trim-reboiler is economically beneficial and below that the employment of bottom reboiler would be more cost effective. The issue concerning the determination of this optimal driving force for a specified system will be addressed in future work.

Subsequently, for the better performing HIDiC-VRCIR column in conjunction with an internal energy driven bottom reboiler, we further propose the two modes of compressors arrangement, namely parallel and series. For the representative system, in which, the boiling point temperatures of the components to be separated are far apart, the series mode of HIDiC-VRCIR column shows a little better overall performance compared to its parallel counterpart. Comparing these two ideal HIDiC-VRCIR configurations, we conclude that the energetic and economic potential of the series mode enhances as the temperature difference (ΔT) between the sink and source increases.

Notation

A = heat exchange area, m^2
F = feeding rate, kmol/s
H = enthalpy, kJ/kmol
L = liquid flow rate, kmol/s
$L^R_{n+n_F}$ = rate of liquid produced in internal HE for (n_F+n)th rectifier stage, kmol/s
m = liquid holdup, kmol
NC = total number of components (= 3)
n_F = feed tray
n_T = top tray/total number of stages
P = pressure, kPa
P_t = total pressure, kPa
Q = heat duty, kW
Q_{Cons} = total heat consumption, kW
$\bar{Q}_{Cons}$ = total heat consumed for the entire operational time, kJ
Q_e = makeup heat supplied externally to trim-reboiler, kW
S = side stream rate, kmol/s
T = temperature, K
t_o = total operational time, s
U = overall heat-transfer coefficient, kW/m^2 K
V = vapor rate, kmol/s
V^S_n = rate of vapor produced in internal HE for nth stripper stage, kmol/s
V_{n_TC} = fraction of overhead vapor rate (V_{n_T}) subjected to compression, kmol/s
V_{n_Ti} = fraction of overhead vapor rate subjected to condensation, kmol/s
x_i = liquid phase mole fraction of species i
y_i = vapor phase mole fraction of species i
ΔP = stage pressure drop, kPa
ΔT = thermal driving force, K
ΔT_{min} = minimum thermal driving force, K
μ = polytropic coefficient
γ = activity coefficient
λ = latent heat, kJ/kmol

Suffix

BR = bottom reboiler
Comp = compressor
Cond = condenser
Cons = heat consumption
HE = internal HE connected between rectifier and stripper in HIDiC
i = inlet/component index
IR = intermediate reboiler
L = liquid
n = tray index
n_F = feed tray
n_T = top tray
o = outlet
R = trim-reboiler
V = vapor
0 = vapor pressure

Abbreviation

CDiC = conventional distillation column
Comp = compressor
CR = compression ratio
HIDiC = heat integrated distillation column
IR = intermediate reboiler
RR = reflux ratio
TV = throttling valve
VRC = vapor recompression column
VRCIR = vapor recompression column with intermediate reboiler

Literature Cited

1. US National Academies Report. 2008. Available at http://americasclimatechoices.org/climate_change_ 2008_final.pdf. Last accessed on 2008.
2. Engelien HK, Skogestad S. Selecting appropriate control variables for a heat integrated distillation system with prefractionator. *Comput Chem Eng*. 2004;28:683–691.
3. Diez E, Langston P, Ovojero G, Ramero MD. Economic feasibility analysis of heat pumps in distillation to reduce energy use. *Appl Therm Eng*. 2009;29:1216–1223.
4. Jana AK. Heat integrated distillation operation. *Appl Energy*. 2010; 87:1477–1494.
5. Kaibel G. Distillation columns with vertical partitions. *Chem Eng Technol*. 1987;10:92–98.
6. Christiansen AC, Skogestad S, Liena L. Complex distillation arrangements: extending the Petlyuk ideas. *Comput Chem Eng*. 1997;21:237–242.
7. Schultz MA, Stewart DG, Harris JM, Rosenblum SP, Shakur MS, O'Brien DE. Reduce costs with dividing-wall columns. *Chem Eng Prog*. 2002:64–71.
8. Olujic Z, Kaibel B, Jansen H, Rietfort T, Zich E, Frey G. Distillation column internals/configurations for process intensification. *Chem Biochem Eng*. 2003;Q. 17:301–309.
9. Kolbe B, Wenzel S. Novel distillation concepts using one-shell columns. *Chem Eng Proc*. 2004;43:339–346.
10. Kiss AA, Pragt H, van Strien C. Reactive dividing-wall columns−how to get more with less resources? *Chem Eng Commun*. 2009; 196:1366–1374.
11. Bravo-Bravo C, Segovia-Hernández JG, Gutiérrez-Antonio C, Duran AL, Bonilla-Petriciolet A, Briones-Ramírez A. Extractive dividing wall column: design and optimization. *Ind Eng Chem Res*. 2010;49: 3672–3688.
12. Kiss AA, Rewagad RR. Energy efficient control of a BTX dividing-wall column. *Comput Chem Eng*. 2011;35:2896–2904.
13. Flower JR, Jackson R. Energy requirements in the separation of mixtures by distillation. *Trans Inst Chem Eng*. 1964;42:T249–T258.
14. Annakou O, Mizsey P. Rigorous investigation of heat pump assisted distillation. *Heat Recov Syst CHP*. 1995;15:241–247.
15. Fonyo Z, Kurrat R, Rippin DWT, Meszaros I. Comparative analysis of various heat pump schemes applied to C_4 splitters. *Comput Chem Eng*. 1995;19:S1–S6.
16. Jana AK, Mane A. Heat pump assisted reactive distillation: wide boiling mixture. *AIChE J*. 2011;57:3233–3237.
17. Kaibel B, Jansen H, Zich E, Olujic Z. Unfixed dividing wall technology for packed and tray distillation columns. *Distillation and Absorption*, *Vol*. 152. 2006:252–266.
18. Dejanovic I, Matijasevic L, Olujic Z. Dividing wall column−a breakthrough towards sustainable distilling. *Chem Eng Process*. 2010;49:559–580.
19. Haselden GG. An approach to minimum power consumption in low temperature gas separation. *Trans Inst Chem Eng*. 1958;36:123–132.
20. Mah RSH, Nicholas JJ, Wodnik RB. Distillation with secondary reflux and vaporization: a comparative evaluation. *AIChE J*. 1977; 23:651–657.
21. Fitzmorris RE, Mah RSH. Improving distillation columns design using thermodynamic availability analysis. *AIChE J*. 1980;26:265–273.
22. Kiran B, Jana AK, Samanta AN. A novel intensified heat integration in multicomponent distillation. *Energy*. 2012;41:443–453.
23. Nakaiwa M, Huang K, Endo A, Ohmori T, Akiya T, Takamatsu T. Internally heat-integrated distillation columns: a review. *Trans Inst Chem Eng*. 2003;81:162–177.
24. Naito K, Nakaiwa M, Huang K, Endo A, Aso K, Nakanishi T, Nakamura T, Noda H, Takamatsu T. Operation of a bench-scale ideal heat integrated distillation column (HIDiC): an experimental study. *Comput Chem Eng*. 2000;24:495–499.
25. 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.
26. Fukushima T, Kano M, Hasebe S. Dynamics and control of heat integrated distillation column (HIDiC). *J Chem Eng Jpn*. 2006;39: 1096–1103.
27. 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;39:6860–6870.
28. Iwakabe K, Nakaiwa M, Huang K, Nakanishi T, Røsjorde A, Ohmori T, Endo A, Yamamoto T. Energy saving in multicomponent

separation using an internally heat-integrated distillation column (HIDiC). *Appl Therm Eng*. 2006;26:1362–1368.
29. 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;8:923–932.
30. Mane A, Jana AK. A new intensified heat integration in distillation column. *Ind Eng Chem Res*. 2010;49:9534–9541.
31. Suphanit B. Optimal heat distribution in the internally heat-integrated distillation column (HIDiC). *Energy*. 2011;36:4171–4181.
32. Shenvi AA, Herron DM, Agrawal R. Energy efficiency limitations of the conventional heat integrated distillation column (HIDiC) configuration for binary distillation. *Ind Eng Chem Res*. 2011;50:119–130.
33. Harwardt A, Marquardt W. Heat-integrated distillation columns: vapor recompression or internal heat integration? *AIChE J*. 2012;58:3740–3750.
34. Felbab N, Patel B, EI-Halwagi MM, Hildebrandt D, Glasser D. Vapor recompression for efficient distillation. 1. A new synthesis perspective on standard configurations. *AIChE J*. 2013;59:2977–2992.
35. Olujic Z, Jodecke M, Shilkin A, Schuch G, Kaibel B. Equipment improvement trends in distillation. *Chem Eng Proc*. 2009;48:1089–1104.
36. Kumar V, Kiran B, Jana AK. A novel multi-stage vapor recompression reactive distillation with intermediate reboilers. *AIChE J*. 2013; 59:761–771.
37. Douglas JM. *Conceptual Design of Chemical Processes, 1st ed*. New York: McGraw-Hill, 1988.
38. Luyben WL. Design and control of distillation columns with intermediate reboilers. *Ind Eng Chem Res*. 2004;43:8244–8250.
39. Jana AK. *Chemical Process Modelling and Computer Simulation, 1st ed*. New Delhi: Prentice-Hall, 2011.

Appendix A

Energy consumption

The total energy consumed (Q_{Cons}) by a heat-integrated column is calculated by adding the reboiler heat load (Q_{R}) plus three times the compressor duty (Q_{Comp}). It implies

$$Q_{\mathrm{Cons}}=Q_{\mathrm{R}}+3\ Q_{\mathrm{Comp}} \tag{A1}$$

The factor of three for the compression duty is assumed to convert the compression work into the thermal energy required to produce an equivalent amount of electrical power.[28]

It should be noted that for the CDiC column, $Q_{\mathrm{Comp}}=0$. As far as HIDiC is concerned, the following form of correlation is used for computing the compressor duty[37]

$$Q_{\mathrm{Comp}}=3.03\times10^{-5}\frac{\mu}{\mu-1}V_{n_{\mathrm{F}}}P_{\mathrm{i}}\left[\left(\frac{P_{\mathrm{o}}}{P_{\mathrm{i}}}\right)^{\frac{\mu-1}{\mu}}-1\right] \tag{A2}$$

In the above equation, the pressure (inlet pressure, P_{i} and outlet pressure, P_{o}) is in $\mathrm{lb_f/ft^2}$, and the vapor inflow rate to the compressor ($V_{n_{\mathrm{F}}}$) is in $\mathrm{ft^3/min}$. The polytropic coefficient (μ) is calculated from Eq. 2. Knowing the Q_{Cons} for CDiC and its heat-integrated counterpart, one can estimate the percent energy savings.

Economic evaluation

The TAC that is usually used as the indicator for economic feasibility of a heat-integrated configuration is expressed as

$$\text{TAC}\ (\$/\text{yr})=\text{operating cost (OC)}+\frac{\text{capital investment (CI)}}{\text{payback period }(\theta)} \tag{A3}$$

The capital cost is estimated by summing up individual equipment cost, determined using the formulas given in Table 1. The operating cost of the compressor is computed as suggested by Douglas[37] based on the bhp (= hp/0.9), and a motor efficiency of 0.6. For the sake of simplicity, operating costs are taken to be identical to utility costs, that is, the number resulting from the summation of electricity (0.084 \$/kW h), steam (17 \$/t), and cooling water (0.06 \$/t) costs for a year having 8000 operating hours.[22]

Appendix B

The following assumptions have been adopted in deriving the mathematical model for both the CDiC and HIDiC columns.

- Perfect mixing and equilibrium on all trays.
- Negligible tray vapor holdups.
- Variable liquid holdup in each tray.
- Hildebrand regular solution model[39] to predict vapor–liquid equilibrium.
- Constant stage pressure drop (0.3 kPa) and efficiency (70%) for all trays.
- Nonlinear Francis weir formula for liquid hydraulics calculations.

Figure 6 represents a typical *n*th tray, showing all incoming and outgoing streams. The plate is fed with a liquid feed mixture and the side streams are withdrawn in both liquid and vapor states. Numbering the stage with the bottom as Stage 1 and the top as Stage n_{T} (=24), the governing equations for the dynamic model of *n*th (subscript *n*) tray of a distillation column can be derived as

nth tray (for CDiC and HIDiC)

Total Mole Balance

$$\dot{m}_n=L_{n+1}+V_{n-1}+F_n-(L_n+S_n^L)-(V_n+S_n^V) \tag{B1}$$

Component (i) Mole Balance

$$\dot{m}_n\dot{x}_{n,\ i}=L_{n+1}x_{n+1,\ i}+V_{n-1}y_{n-1,\ i}+F_nz_{n,\ i}-(L_n+S_n^L)x_{n,\ i}-(V_n+S_n^V)y_{n,\ i} \tag{B2}$$

Energy Balance

$$\dot{m}_n\dot{H}_n^L=L_{n+1}H_{n+1}^L+V_{n-1}H_{n-1}^V+F_nH_n^F-(L_n+S_n^L)H_n^L-(V_n+S_n^V)H_n^V \tag{B3}$$

Equilibrium (Species i)

$$P_t y_{n,\ i}=\gamma_{n,\ i}P_{n,\ i}^0 x_{n,\ i} \tag{B4}$$

Here, the dot symbol (.) is used to represent the time derivative. The time derivative of the multiplication of two variables, say m and x, is denoted here by $\dot{m}\dot{x}(=d(mx)/dt)$.

Internal HE (for HIDiC)

As shown in Figure 1, suppose the *n*th stage of stripper is coupled with $(n_{\mathrm{F}}+n)$th stage of rectifier. Accordingly, we have

$$Q_{\mathrm{n}}=\mathrm{UA}\ (T_{n+n_{\mathrm{F}}}-T_n) \tag{B5a}$$

with

$$Q_{\mathrm{HE}}=\sum_{n=1}^{n=n_{\mathrm{F}}}Q_n \tag{B5b}$$

Stripping Section

$$V_n^{rS} = \frac{Q_n}{\left(\sum_{i=1}^{N_c} y_i \lambda_i\right)_n} \tag{B5c}$$

Rectifying Section

$$L_{n+n_F}^{R} = \frac{Q_n}{\left(\sum_{i=1}^{N_c} x_i \lambda_i\right)_{n+n_F}} \tag{B5d}$$

Compressor (for HIDiC)

Equation A2 is used for computing the compressor work (Q_{Comp}) and Eq. 2 for the polytropic coefficient (μ). By rearranging Eq. 1, one can compute the temperature of the compressed overhead vapor as

$$T_O = T_i \left(\frac{P_o}{P_i}\right)^{\frac{\mu-1}{\mu}} \tag{B6}$$

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