A New Technique for Recovering Energy in Thermally Coupled Distillation using Vapor Recompression Cycles

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Even though it has been proved that a fully thermally coupled distillation (TCD) system minimizes the energy used by a sequence of columns, it is well-known that vapor/liquid transfers between different sections produce an unavoidable excess of vapor (liquid) in some of them, increasing both the investment and operating costs. It is proposed here to take advantage of this situation by extracting the extra vapor/liquid and subjecting it to a direct/reverse vapor compression cycle. This new arrangement restores the optimal operating conditions of some of the affected sections with energy savings of around 20–30% compared with conventional TCD columns. Various examples, including the direct and reverse vapor recompression cycles, are presented. Furthermore, in each example, all possible modes of distillation (direct, indirect and Petlyuk distillation) with and without vapor recompression cycles (VRC) are compared to ensure that this approach delivers the best results. © 2013 American Institute of Chemical Engineers *AIChE J*, 59: 3767–3781, 2013
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Introduction

We live in a society where any activity, whether work or leisure, requires the consumption of large amounts of energy. Present global energy consumption is estimated to be 12,000 MToe (million tons of oil equivalent), with a 50% increase expected over the next 30 years.[1] Energy consumption in the industrial sector represents approximately 28% of global energy use. Within this sector, the chemical industry accounts for approximately 20%, which represents about 5.6% (0.90 TW/year) of the total energy consumed in the world. In the chemical industry, separation processes are the most energy intensive. Among the different separation techniques, distillation is the most important and commonly used in the chemical and petrochemical industry. Distillation handles more than 90% of separations[2] and this trend seems unlikely to change in the near future. Mix et al.[3] calculated that distillation processes consumes about 60% of the total energy in the chemical and petrochemical industry. In conclusion, it is estimated that distillation processes accounts for about 3% of global energy use.[4,5] Therefore, any improvement in distillation efficiency will likely have an important global effect on energy consumption.

Despite its widespread use, distillation is energetically inefficient.[6–8] Heat (used as separating agent) is conventionally supplied in the reboiler at the highest process temperature, and removed in the condenser where the temperature is minimum. Therefore, the heat recovered in the condenser cannot be reused for heating other parts of the distillation unit.

As a result of the importance of distillation and its low efficiency, a large number of alternatives have been proposed in an attempt to increase efficiency and/or recover part of the energy degraded by distillation.

To improve the thermal efficiency of a distillation column a good number of interesting alternatives have been proposed. Without embarking on a comprehensive review, these include:

a. Intercoolers-interheaters in order to reduce the reboiler or condenser heat loads—the case of condensers in the rectifying section are of special interest if refrigeration at subambient temperature is needed in the condenser.[9–13] The objective is enhanced reversible operation of the column.
b. Heat pumps and vapor recompression schemes.[14–18]
c. Secondary reflux and vaporization.[19]
d. Multiple-effect heat cascading for distillation columns.[20–23] Where the condensing temperature is higher than the reboiling temperature, the condensing overhead vapors of one distillation column can serve as the reboiler duty for another column. This creates the equivalent of a multieffect evaporator system, except that distillation columns are used, rather than direct evaporation.
e. Heat integration.[24–26] The idea is to exchange heat between the condenser and the reboiler of different distillation columns. The operating pressure of some columns can be adjusted to obtain the adequate driving force.
f. Internally heat integrated distillation columns (HIDiC).[27–32] Here rectifying and stripping sections are separated. The rectifying section is compressed—and, consequently, temperature increase— and rectifying and stripping sections are totally or partially heat integrated, again in an attempt to approximate reversible distillation behavior.

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g. Thermally coupled distillation (TCD).[26,33–43] Some heat exchangers (reboiler or condensers) are removed and replaced by thermal couples. TCD produces a large number of alternative distillation column sequences (much larger than classical column sequencing which can be considered a special case of TCD). This introduces a large number of new and interesting alternatives, but at the cost of increasing the complexity of the problem.

Excellent reviews of the various energy-efficient distillation techniques can be found in Jana,[44] Fonyo et al.[45] and Nakaiwa el al.[46]

Even though a fully thermally coupled (FTC) configuration minimizes energy consumption, it cannot be concluded that FTC configurations are always superior when compared to sequences of simple columns or to partially thermally coupled configurations (PTC). Instead, the optimum configuration will depend on the specific mixture and feed conditions for at least the following reasons:

1. The energy is supplied and removed under the worst conditions: supplied at the highest temperature in the reboiler, and removed at the lowest temperature in the condenser. In most cases, this precludes the use of lower cost utilities, that is, medium- or low-pressure steam in the reboiler. This is especially true for the condenser if the most volatile component must be condensed at subambient temperature, which rules out making use of cooling water.
2. In FTC systems the minimum vapor flow is that of the most difficult separation.[47,48] The thermal couples transfer the vapor between columns and, therefore, some column sections could have large diameters.
3. In FTC sequences the total number of column sections is larger than in the case of sequences of simple columns. A detailed discussion on the number of column sections needed for a given separation can be found in the following references.[26,33,37,38,49]
4. Operation is also more difficult due to the large number of interconnections between the columns.

In this article, we propose to convert the inherent inefficiency of some TCD sequences—the excess vapor/liquid flows in certain sections resulting from the vapor liquid transfer by thermal couples—in an advantage by further integrating the system, decreasing the energy and investment costs in the process. The basic idea involves withdrawing the excess vapor (liquid) from the column section that, as a consequence of thermal couples, operates suboptimally. This restores the optimal operating conditions of the affected column section and consequently reduces the column diameter and utility consumption. The resulting vapor (liquid) stream is used in a vapor recompression cycle (VRC) or a reverse-vapor recompression cycle (R-VRC), reducing the utility consumption at the cost of introducing a compressor.

The rest of the article is organized as follows. The source of inefficiency in TCD systems that motivated this work is explained in detail. At this point, the two configurations based on the vapor recompression cycle are introduced. The capabilities of the approach proposed are then illustrated through two case studies, one of which corresponds to an excess of vapor stream in the stripping section and the other to an excess of liquid stream in the rectifying section. Finally, at the end of the article, we discuss the conclusions that can be drawn from this work.

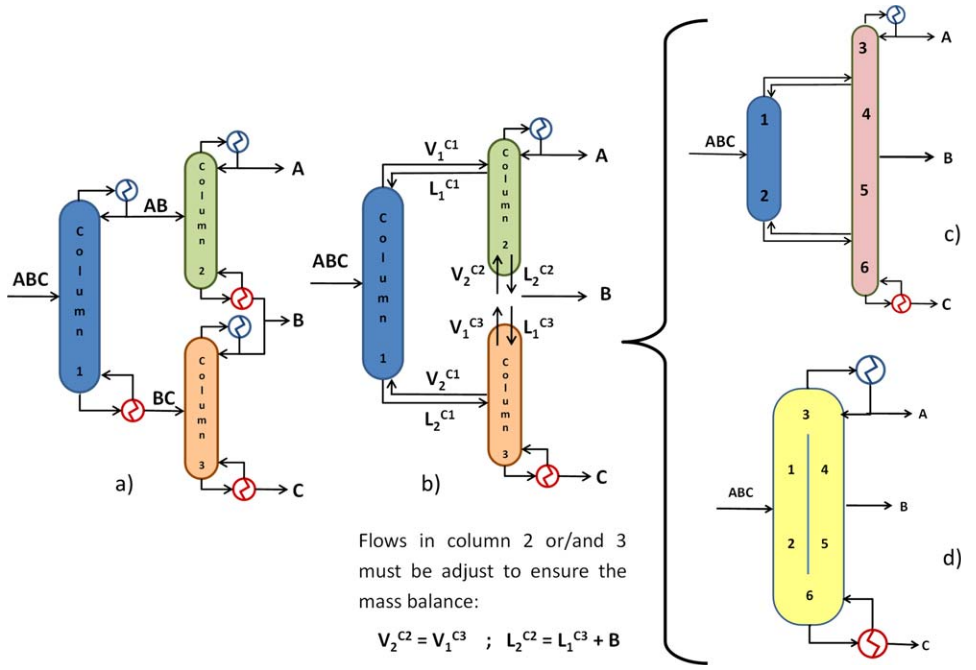
Inefficiency in thermally coupled distillation systems

The literature documents various approaches to the design of TCD systems, ranging from three components[50–53] to N component mixtures.[26,37,38,49,54,55] In order to clearly illustrate the problem, for the sake of simplicity, but without loss of generality we will focus on a three component Petluyk arrangement (see Figure 1). The extension to more complex TCD arrangements is straightforward and based on the same principles. Consider a three component mixture (ABC) having no azeotropes and sorted by decreasing relative volatilities (A is the most volatile and C the least). Independently of design procedure, it is possible to identify three separation tasks for this system: Separate AB from BC (AB/BC) where component B is optimally distributed between condenser and reboiler. Separate A from B, and separate C from D (see Figure 1).

Assume that each one of the three separation tasks is designed and optimized independently. In that case, the first separation task (AB/BC) is usually operated in "transitions split", also called preferred separation, which guarantees minimum vapor flow inside the column. Then, columns for separations A/B and B/C can be designed.

To design the A/B and B/C separations it is important to notice that the connection with the first column is through a pair of streams (a vapor and a liquid stream). A good way of dealing with this involves following the procedure described by Carlberg and Westerberg.[56] They showed, in the context of an ideal system, that the two streams that connect the rectifying section of the first column (AB/BC) with the second column (A/B) can be substituted by a single stream whose flow is the net flow (V1-L1 referred to Figure 2), and whose thermal state is superheated vapor. Similarly, the two streams that connect the stripping section of the first column with the third column (B/C) can be substituted by a single stream whose flow is the net flow (L2-V2, referred to Figure 2), which is subcooled. Carlberg and Westerberg[56] also showed how to calculate the degree of superheating or subcooling of these equivalent streams. Navarro et al.[57] showed that the degree of superheating or subcooling can be so high that this approach cannot be directly implemented in a process simulator. However, they also showed that a superheated (subcooled) stream is equivalent to a saturated stream plus (minus) an energy stream (See Figure 2c). Following this approach they proved that it is possible to simulate complex nonideal TCD systems without introducing recycling (avoiding tear streams and complex iterations), and with errors in heat loads and internal vapor flows that average 2–3%, but rarely over 5%. This is the approach we will follow in this article.

The simulation of a Petlyuk column entails that mass balances be satisfied in all thermal couplings. While the couplings between columns 1 and 2 and between 1 and 3 are achieved by sidestream extraction, the connection between columns 2 and 3 is made directly between them. As the system must exhibit the same behavior before and after the coupling, both columns must operate at the same internal flows $V_2^{C_2}=V_1^{C_3}$. Unfortunately, this situation rarely occurs. On the contrary, the vapor flows of the optimized columns are different, either $V_2^{C_2} > V_1^{C_3}$ or $V_2^{C_2} < V_1^{C_3}$. It is necessary to increase the internal flows either in column 2 or column 3 depending on which column dominates (See Figure 1b). For example if $V_2^{C_2} > V_1^{C_3}$, then $V_1^{C_3}$ must be increased by $DV=V_2^{C_2}-V_1^{C_3}$ to make both flows equal ($L_1^{C_3}$ must also be increased by DV), which increases the diameter of column 3,



Flows in column 2 or/and 3 must be adjust to ensure the mass balance:

$V_2^{C2} = V_1^{C3}$; $L_2^{C2} = L_1^{C3} + B$

Figure 1. Construction of the Peltyuk (c), and divided wall columns (d) by decomposition into basic tasks (b) and further elimination of heat exchangers.

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

the reboiler duty, and as a result its fixed and variable costs. Similarly, if the "dominant column"—the column with largest internal flows—is column 3, the adjustment of flows in column 2 increases the condenser duty and the diameter of column 2.

It is worth remarking that instead of following a sequential approach it is possible to optimize the three columns simultaneously in order to mitigate the effect of flow imbalances in the connection points (i.e., the distribution of flows through the thermal couples could reduce excess duties if some of the separations took place under suboptimal conditions compared to the isolated separation tasks). In any event, except in some special cases, at least one separation task always occurs under suboptimal conditions (larger internal flows and therefore larger duties) compared to operation in isolation from the rest of the system.

There are at least two alternatives to try to improve the efficiency of the aforementioned TCD systems:

a. Introduce a heat exchanger at the connection point (see Figure 3) —a reboiler if the dominant column is column 2, and a condenser if the dominant column is column 3. In that way, all the column sections are operated in their optimal conditions. An energy balance shows that duty of the new heat exchanger is comparable to the extra duty in the original Petlyuk due to the overflows (equal if we assume constant enthalpies). There is an added advantage; the temperature at which the heat must be supplied (removed) is between the

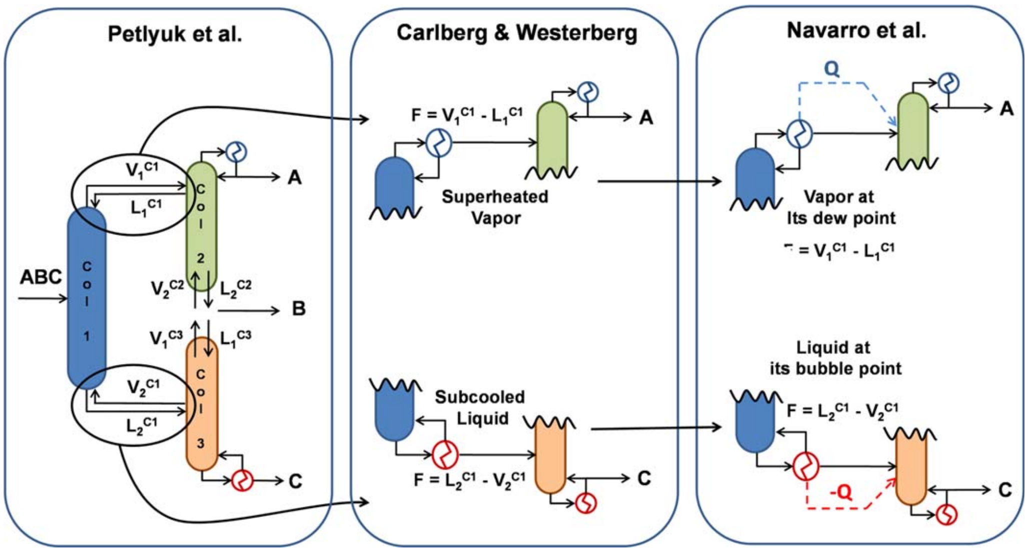


Figure 2. Equivalent configurations for a thermal coupling.

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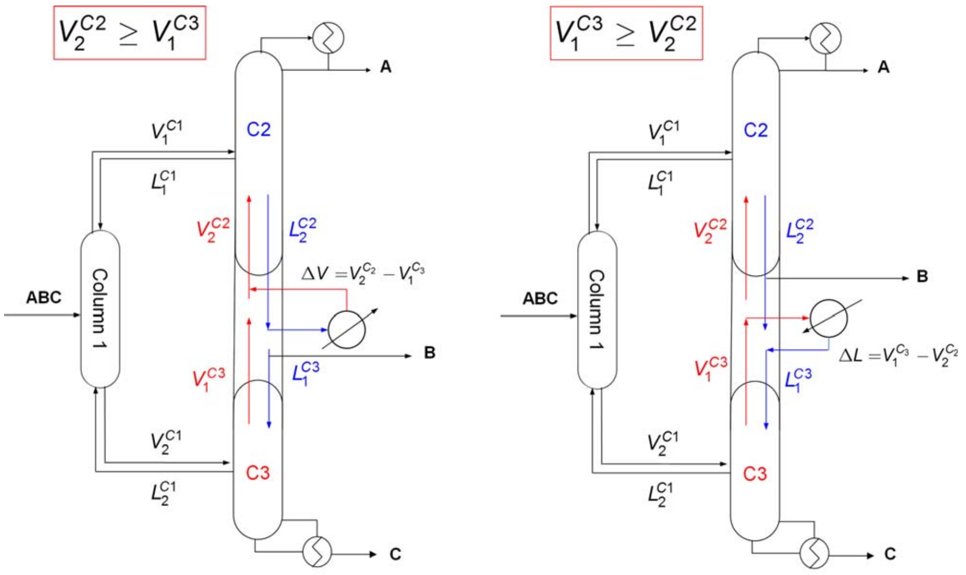

(a) (b)

Figure 3. Petlyuk configuration with an intermediate reboiler (a), and an intermediate condenser (b).

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temperature in the condenser and the temperature in the reboiler. Therefore, in some situations we can use a cheaper utility (i.e., if we have to heat we will do it at lower temperature than in the reboiler; if we have to cool we will do it at a higher temperature than in the condenser). Of course, we also have to purchase the new heat exchanger. An economic analysis is necessary to determine the best option.

b. The ideal situation would be to withdraw the extra vapor (liquid) and use it as a hot (cold) stream elsewhere in the process and then return the condensed (vaporized) stream to the column. Unfortunately this is not always possible.

In this article we propose to use this extra vapor in a vapor recompression cycle (VRC) or the extra liquid in a reverse vapor recompression cycle (RVRC).

Vapor recompression and reverse vapor recompression cycles in thermally coupled distillation

In a standard vapor recompression cycle (SVRC) (see Figure 4) the vapor leaving the top of the column is compressed isentropically, causing also an increase in temperature that provides the driving force for heat transfer to the bottom liquid. At the same time it elevates the dew point of the overhead vapor, allowing its latent heat to be used at a higher temperature. This overhead vapor stream is heat exchanged with the liquid leaving the bottom of the column, which partially (or totally) vaporizes the latter and, in turn, provides vapor load to the column and condenses by itself (totally or partially). This condensed stream is then subcooled in the condenser to such an extent that when its pressure is dropped back down to the column pressure, it does not vaporize. Ideally, energy is only added in the compressor and removed in the condenser. The major drawback of SVRCs is that the difference in temperatures between condenser and reboiler should not be too large (say a maximum of around 30°C), otherwise the compression ratio becomes too large—multistage compression might then become necessary—and compressors are some of the most expensive devices in chemical processes. A similar situation could appear in HICiC.[58] If the temperature difference between the rectifying and stripping sections is large, then the pressure increase of the rectifying section to heat integrate both sections must be also large. Again the cost of compressor could dominate the system performance.

If in the petlyuk configuration there is an excess of vapor in the rectifying section of column 3 it is possible to extract this excess and isentropically compress it until the temperature is high enough to permit heat exchange with the bottom stream. Some saturated vapors condense on isentropic compression (a detailed explanation can be found in the work by Felbab et al.[14]), and in this case some preheating before compression might be necessary. In contrast to SVRC, we cannot expect all the heat duty in the reboiler to be supplied by the compressed vapor, and, therefore, the hot utility cannot be removed, but merely reduced. The condensed vapor is

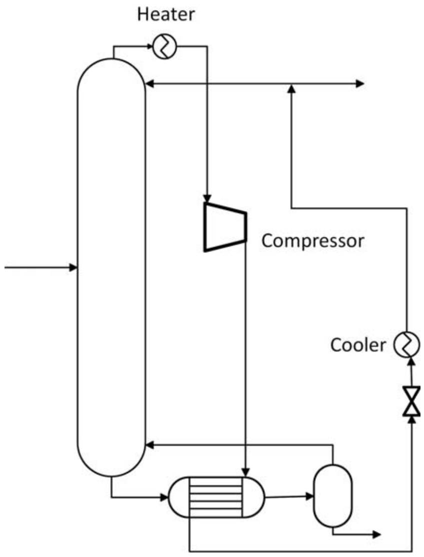

Figure 4. Scheme of a standard vapor recompression cycle.

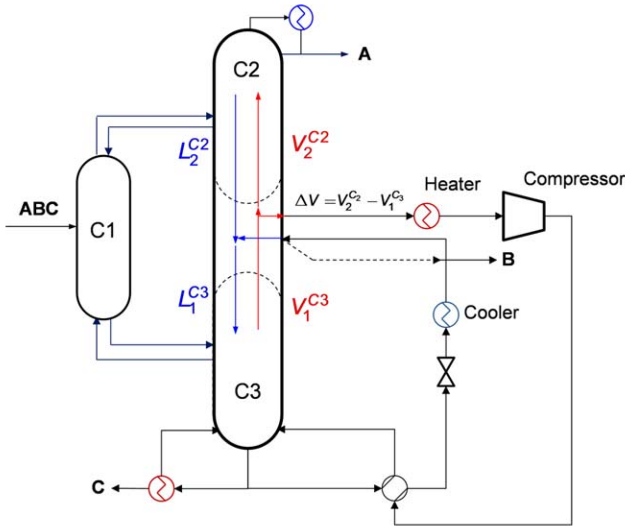

Figure 5. Scheme of a Vapor Recompression Cycle using the excess of Vapor in rectifying section of column 3.

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

subcooled if needed and then expanded to the column pressure. A part of this stream is the intermediate product (see Figure 5), and the rest is returned to the column to provide the extra reflux needed by column 3 (the reflux to column 3 is provided by the liquid entering from the stripping section of column 2 plus the returned liquid after the VR).

There are some aspects of the new VRC that deserve special attention:

1. The difference in temperature between the reboiler and the vapor withdrawn from the column is lower than between condenser and reboiler; as a consequence it is possible implement this new VRC in columns where SVRC is not economically viable.
2. There is a synergic effect between the TCD (Petlyuk column in the example) and the VRC: TCD is returned to its optimal operating conditions (i.e., smaller column diameters, reduced condenser duties) and energy is saved with the VRC. So we have two sources of improvement working together: the improved efficiency of the TCD and the energy savings of the VRC.
3. The synergic effect commented previously enhances the performance of the new VRC scheme. Therefore, depending on the reduction in capital and operating costs in the TCD scheme it might be of interest to implement VRC with larger temperature differences. However, of course this is case dependent and a detailed economic analysis is necessary.
4. There are two reasons why the VRC is expected to perform better as the mass imbalance in the connection between sections becomes larger: (1) The extent to which heat is exchanged in the reboiler increases with the vapor flow withdrawn from the column, and (2) the return of some column sections to their optimal operating conditions have a larger impact on the total cost. It bears mentioning here that even though the Petlyuk configuration achieves the lowest total energy consumption, if certain sections operate far from optimally, it is likely that the Petlyuk configuration will not be the best from a total cost point of view. Using a VRC avoids this inefficiency, but in general deciding which column sequence is the best (with or without VRCs) requires a detailed study of all the alternatives.
5. The performance of the VRC depends on the relative utility costs of both the heating in the reboiler and the power needed to drive the compressor and the new equipment, but mainly the compressor. A detailed economic analysis is always necessary.
6. The direct VRC is not always possible. It requires that column 3 be dominant.

If the dominant column is column 2, it is still possible to use a reverse vapor recompression cycle (RVRC). In this case the excess saturated liquid is withdrawn as a side stream from the connection point between columns 2 and 3 (see Figure 6). Part of this liquid is the product with intermediate volatility (B); the rest is expanded, until its temperature reaches a value low enough to be used as a cooling utility in the condenser. As in the case of VRC, we cannot expect all the cooling duty to be supplied by the latent heat of this stream; therefore, we must resort to using some external cooling utility. After the stream is completely vaporized, it is introduced into a compressor, where the pressure is isentropically increased until it is restored to the operating pressure of the column. In this case, because the compressor efficiency is less than 100%, (typically around 75%) overheating occurs in the outlet stream of the compressor and, thus, guarantees the appearance of a vapor stream in the compressor output. Finally, this vapor is introduced in the column at the same stage from which it was extracted, and this way provides the required extra vapor flow that ensures correct behavior in the rectifying section of the column.

If the condenser is cooled by water or air (or any other cheap utility), it is obvious that a RVRC is economically unfavorable even in the case of a significant reduction in the heat utility and column diameter (an intermediate reboiler would likely produce the same effect). However, if subambient cooling is needed in the condenser (refrigeration cycles

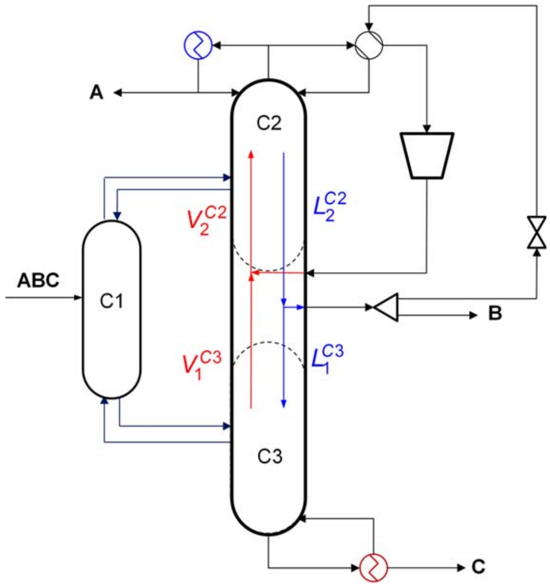

Figure 6. Scheme of a Reverse Vapor Recompression Cycle using the excess of liquid in the stripping section of column 2.

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

Table 1. Specifications for the Hot and Cold Utilities

Utilities	T_{in} (°C)	T_{out} (°C)	Cost ($/GJ)[a]
Steam			
Atmospheric Pressure (1 bar)	100	100	6,67
Low Pressure (6 bar)	160	160	7,78
Medium Pressure (11 bar)	184	184	8,22
High Pressure (42 bar)	254	254	9,83
Water	20	40	0,354
Refrigeration			
Low Temperature	−20	−20	7,89
Very Low Temperature	−50	−50	13,11

[a] All prices are referred to 2002

are expensive) RVRC becomes an attractive alternative: in general, the lower the condenser temperature, the better the expected performance of the RVRC.

The VRC and RVRC can be implemented in any thermally coupled sequence in which certain sections are not operating optimally. A detailed description of how to design and optimize TCD sequences can be found, for example in the following references.[26,37,38,59,60] From those models it is easy to identify the affected column sections. Although the Petlyuk configuration is convenient for illustrating VRC cycles, it is in general not put into practice in industry because of difficulty of operation. Especially challenging is the control of vapor flows between the columns. Vapor AB flows from the top of the prefractionator (column1) to the upper feed level in the product column (column 2). This implies that the pressure in the top of the prefractionator is greater than the pressure in the upper section of the product column. On the other hand, vapor BC has to be transferred from the lower section of the product column to the bottom of the prefractionator (column 3). Therefore, the pressure in the bottom of the prefractionator has to be lower than the pressure in the lower section of the product column.[35] The pressure in the prefractionator is neither uniformly higher nor uniformly lower than the pressure in the product column. However, the Petlyuk arrangement has two thermodynamically equivalent configurations without that problem,[35,61] and it is also equivalent to a divided wall column (DWC) (See Figure 1). In other words, the Petlyuk arrangement is convenient for simulation purposes although the actual implementation could be any of the thermodynamically equivalent configurations, including the DWC. This can be extended to more complex TCD arrangements (sequences involving N components, $N > 3$). Caballero and Grossmann[61] proved that any sequence of separation tasks can always be arranged in a set of distillation columns in which the vapor flows always from higher to lower pressures, although for simulation purposes any of the thermodynamically equivalent configurations can be used.

Examples and Implementation Details

In this section, two examples corresponding to the VRC and RVR configurations are shown. The installation of a VRC or RVRC involves the use of expensive equipment, (i.e., compressors); and a detailed economic analysis must be performed to clearly establish the advantages of a given design. Therefore, it is necessary to estimate the additional cost due to the purchase and installation of this new equipment. The equipment cost is calculated using correlations from the literature, and to this end we use the correlations given by Turton et al.[62] Finally, we update the prices to 2012 using the "Chemical Engineering Plant Cost Index" (CEPCI). The annual cost of the equipment is calculated for a time horizon ($n = 10$ years) and an annual interest rate (i) of 8%[63] using the following expression

$$\text{Annualized capital cost} = \text{capital cost} \cdot \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$\text{where} \quad i = \text{fractional interest rate per year}$$

$$n = \text{number of years}$$

All the simulations were done using the sequential modular simulator ASPEN—HYSYS with the Soave-Redlich-Kwong (SRK) equation of state and default values. The hot and cold utilities used are shown in Table 1.

Example 1. VRC

The first case study deals with the separation of a mixture of aromatics (p-xylene, cumene, 1,2,4-trimethylbenzene). We follow a sequential approach to optimize each of the individual column sections. The main stream specifications are shown in Table 2.

First, a short-cut distillation model is used to find the number of equilibrium stages and the feed tray location of each column. Then we simulate and calculate the energy consumption and costs associated with the separation using a conventional Petlyuk column. The flow sheet for the simulated Petlyuk column is shown in Figure 7.

The next step is to study the effect of introducing the VRC into the aforementioned Petlyuk column. With this aim, we simulate and calculate the energy consumption and cost associated with this system. A minimum temperature difference of 15°C is assumed between the compressed vapor stream and the liquid stream entering the reboiler. An adiabatic efficiency of 75% is assumed in the compressor. The flow sheet for this configuration is shown in Figure 8.

The results obtained for both systems are shown in Tables 3 and 4.

As expected, the introduction of the VRC in the conventional Petlyuk column generates significant energy savings. It is remarkable that the energy savings in the reboiler are over 18% (0.38 MM €/year). There is also a comparable reduction in the energy consumed by the condenser. As we anticipated, the installation of the VRC increases capital cost (equipment), exactly by 22% (0.06 MM €/year), but the global energy cost is reduced by 11% (0.24 MM €/year).

Table 2. Streams Specifications for the Separation System

	P (atm)	T (°C)	Molar Flow (kmol/h)	Composition		
				p-xylene	cumene	1,2,4-trimethylbenzene
Feed ABC	1,00	153,7	200,00	0,3000	0,3000	0,4000
Product A	1,00	139,1	60,00	**0,9998**	0,0002	0,0000
Product B	1,00	153,7	60,03	0,0010	**0,9977**	0,0013
Product C	1,00	169,4	79,97	0,0000	0,0006	**0,9994**

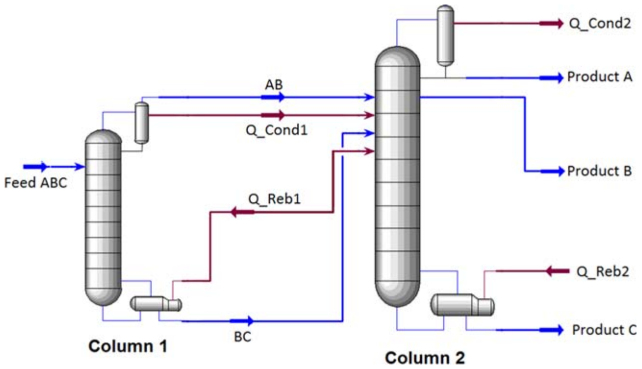

Figure 7. Flow sheet for the simulation of the Petlyuk configuration column.

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

The capital investment of the equipment is recovered in fewer than 3 years of operation. If we assume that annual capital investment payments are spread equally over time, the annual cost decreases by 0.18 MM € per year.

The Petlyuk configuration is not the only sequence for separating a three component mixture. There are two more distillation sequences, with or without thermal couples, capable of separating a three component mixture into three relatively pure products using simple columns: the direct and indirect sequence. A direct separation sequence with a thermal couple is thermodynamically equivalent to a column with a side stripper, while the indirect separation sequence with a thermal couple is equivalent to a column with a side enricher.[64] Furthermore, it is possible to use VRC in any of these configurations (for this mixture, the VRC is only recommended for direct distillation). To enable a comparison of results with those of the Petlyuk sequence with VRC, we evaluate the same separation task using the direct, indirect and direct with VRC sequences (Figure 9).

The results obtained for each configuration are presented in detail in Appendix A. The outcomes of the simulations are summarized in Figure 10. These results show that the configuration achieving the lowest total annual cost is the Petlyuk distillation with VRC. It is noteworthy that the energy savings outweigh the additional cost associated with the purchase and installation of VRC for the Petlyuk column and the direct distillation sequence (Table A3).

Example 2: RVRC

In this example we study the separation of three light hydrocarbons: ethylene, ethane and propane. Again, we use

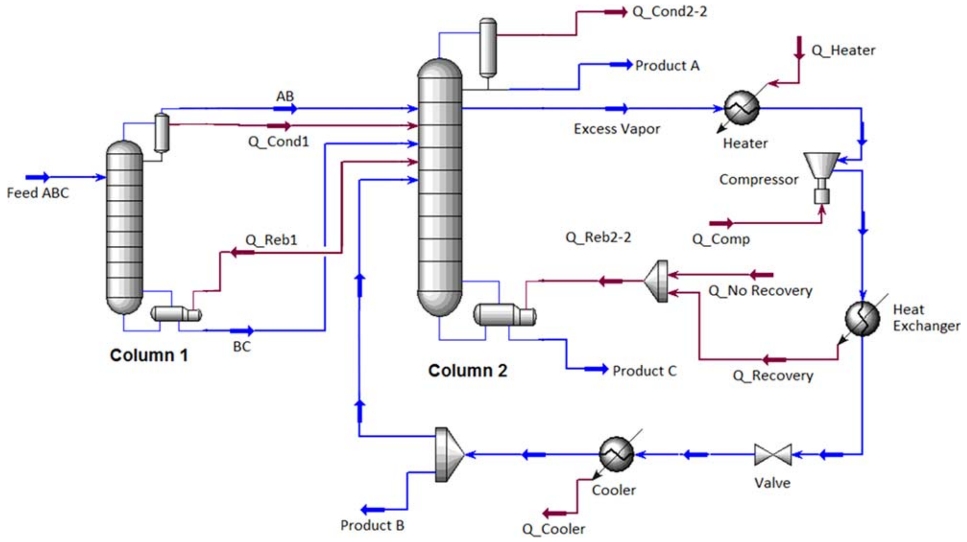

Figure 8. Simulation of Petlyuk configuration column with VRC.

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

Table 3. Conventional Petlyuk Distillation column: Capital and Energy Cost

EQUIPMENT						
COLUMNS						
	Column 1	Column 2	CONDENSER		REBOILER	
V (m^3)	95,2	316,7	A (m^2)	222,1	A (m2)	1273,1
Cost (€)	359994	981392	Cost (€)	128751	Cost (€)	359280
Annual cost (€/year)	53650	146256	Annual cost (€/year)	19188	Annual cost (€/year)	53543
TOTAL ANNUAL COST			ENERGY			
			CONDENSER		REBOILER	
Equipment	272637		Energy (kw)	8772	Energy (kw)	8826
Energy	2175186		Cold Utility	Water	Hot Utility	MP Steam
Total Cost	*2447823*		Energy Cost (€/year)	89284	Energy Cost (€/year)	2085902

Table 4. Conventional Petlyuk Distillation with VRC: Capital and Energy Cost

EQUIPMENT						
COLUMNS						
	Column 1	Column 2	CONDENSER		REBOILER	
V (m^3)	95,2	278,2	A (m^2)	183,1	A (m^2)	1042,5
Cost (€)	359994	1002380	Cost (€)	127119	Cost (€)	336620
Annual cost (€/year)	53650	149384	Annual cost (€/year)	18945	Annual cost (€/year)	50166
HEATER			HEAT EXCHANGER		COOLER	
A (m^2)	10,0		A (m^2)	534,0	A (m^2)	7,6
Cost (€)	15861		Cost (€)	219988	Cost (€)	15051
Annual cost (€/year)	2364		Annual cost (€/year)	32785	Annual cost (€/year)	2243
COMPRESSOR						
Cost (€)	151432					
Annual cost (€/year)	22568					
ENERGY						
COMPRESSOR			CONDENSER		REBOILER	
Energy (kw)	145		Energy (kw)	7231	Energy (kw)	7227
Utility	Electricity		Cold Utility	Water	Hot Utility	MP Steam
Energy Cost (€/year)	69368		Energy Cost (€/year)	73595	Energy Cost (€/year)	1708072
TOTAL ANNUAL COST			COOLER		HEATER	
			Energy (kw)	338	Energy (kw)	299
Equipment	*332104*		Cold Utility	Water	Cold Utility	HP Steam
Energy	*1938855*		Energy Cost (€/year)	3441	Energy Cost (€/year)	84378
Total Cost	*2270959*					

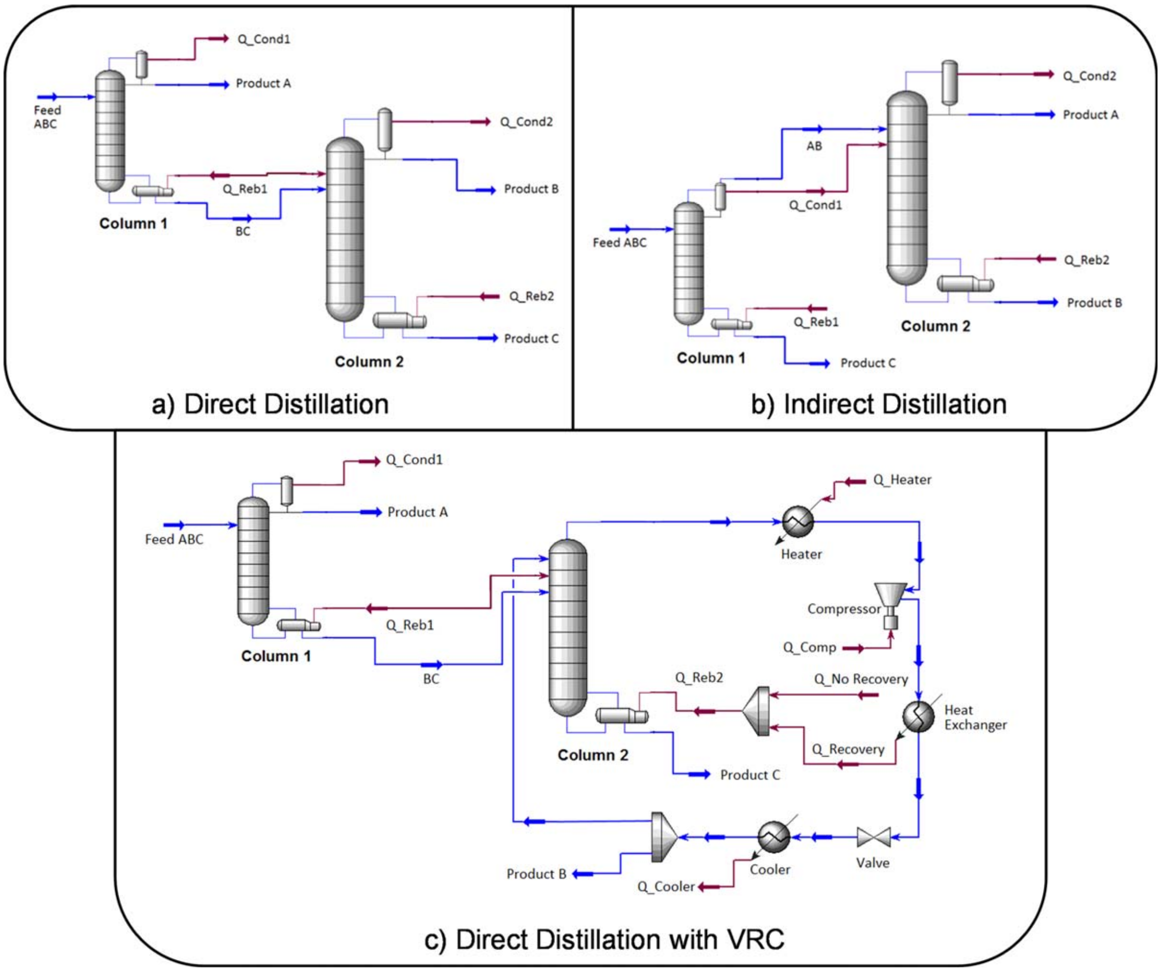

Figure 9. Flow sheet for the direct sequence with and without VRC and for the indirect sequence.

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

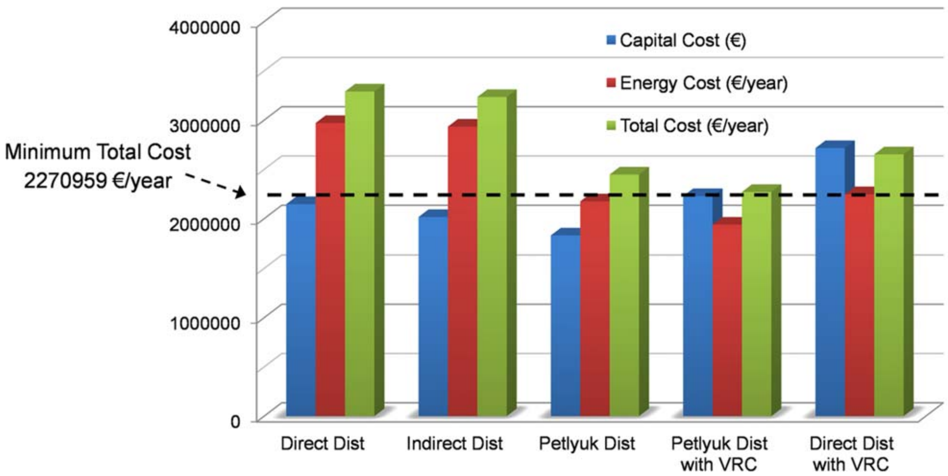

Figure 10. Capital cost of equipment and annualized energy and total costs for the distillation systems studied in example 1.

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

Table 5. Specifications for the Streams in the Separation System

	P (atm)	T (°C)	Molar Flow (kmol/h)	Composition Ethylene	Ethane	Propane
Feed	20,00	1,5	2000,0	0,3000	0,3000	0,4000
Product A	20,00	−28,7	600,8	**0,9977**	0,0023	0,0000
Product B	20,00	−7,2	599,4	0,0009	**0,9977**	0,0014
Product C	20,00	57,1	799,8	0,0000	0,0007	**0,9993**

the sequential optimization simulation methodology for a Petlyuk/DWC. Table 5 shows the main specifications for the streams involved in the simulation.

First, a conventional Petlyuk arrangement is simulated and optimized (Figure 7). The energy consumption and costs associated with this separation are shown in Table 6. Then, we study the effect of introducing the RVRC using the flowsheet shown in Figure 11. A summary of the results obtained are presented in Table 7. As in the previous example we assume a minimum approach temperature of 15°C for heat exchange and a 75% adiabatic efficiency in the compressor.

The results lead to similar conclusions as in the first case study. First, the introduction of the RVRC in the conventional Petlyuk column generates significant energy savings. Indeed, the energy savings in the reboiler are greater than 35% (1.18 MM €/year). This reduction in energy consumption is also matched by the condenser. As expected, the installation of the RVRC increases capital cost by 38% (0.24 MM €/year), but the global energy cost falls by 28% (2.38 MM €/year). The capital investment could be recovered in the first year of operation, and after subtracting the fraction of the total depreciable capital of the equipment, the annual cost decreases by 2.14 MM € per year.

Again, for this second case study, there are also a number of distillation sequences for separating this mixture. Furthermore, it is possible to use RVRC in any of these configurations (for this mixture, the RVRC is only recommended for indirect distillation). For comparison purposes, we simulate the same separation task with the direct and indirect sequences (Figure 9a and 9b, respectively) and the indirect sequence with RVRC (Figure 12).

The results obtained for each configuration are presented in detail in Appendix A2. The costs associated with each sequence are shown in Figure 13.The results show that the Petlyuk with RVRC configuration achieves the lowest total annual cost. As in the previous case study, the savings in energy outweigh the additional cost associated with the purchase and installation of RVRC in both the Petlyuk column as well as indirect sequence. The lowest energy costs are again obtained by using the Petlyuk column in combination with RVRC.

Conclusions

Thermally coupled distillation is an attractive alternative to conventional column sequencing because the energy and

Table 6. Conventional Petlyuk Distillation Column: Capital and Energy Cost

EQUIPMENT						
COLUMNS	Column 1	Column 2	CONDENSER		REBOILER	
V (m^3)	49,6	287,4	A (m^2)	1804,0	A (m^2)	817,1
Cost (€)	521794	2941774	Cost (€)	471174	Cost (€)	269591
Annual cost (€/year)	77763	438411	Annual cost (€/year)	70219	Annual cost (€/year)	40177
TOTAL ANNUAL COST			ENERGY			
			CONDENSER		REBOILER	
Equipment	*626570*		Energy (kw)	13940,5	Energy (kw)	16561,6
Energy	*8430906*		Cold Utility	Very Low Temp Refrigerant	Hot Utility	Atmospheric Press. Steam
Total Cost	*9057476*		Energy Cost (€/year)	5254756	Energy Cost (€/year)	3176150

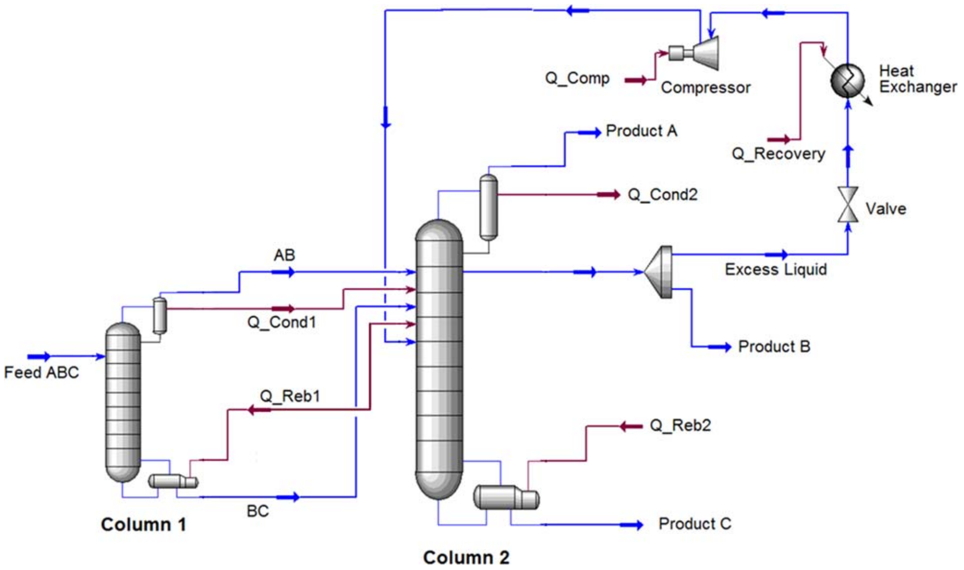

Figure 11. Flow sheet for the simulation of the Petlyuk column with RVRC.

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

Table 7. Conventional Petlyuk Distillation with RVRC: Capital and Energy Cost

EQUIPMENT						
COLUMNS						
	Column 1	Column 2	CONDENSER		REBOILER	
V (m^3)	49,6	257,7	A (m^2)	1168,5	A (m^2)	512,7
Cost (€)	521794	2354008	Cost (€)	343114	Cost (€)	202340
Annual cost (€/year)	77763	350817	Annual cost (€/year)	51134	Annual cost (€/year)	30155
COMPRESSOR			HEAT EXCHANGER			
			A (m^2)	6844,1		
Cost (€)	946032		Cost (€)	1474823		
Annual cost (€/year)	140987		Annual cost (€/year)	219792		
ENERGY						
COMPRESSOR			CONDENSER		REBOILER	
Energy (kw)	1365		Energy (kw)	9011	Energy (kw)	10422
Utility	Electricity		Cold Utility	Very Low Temp Refrigerant	Hot Utility	Atmospheric Pres Steam
Energy Cost (€/year)	654055		Energy Cost (€/year)	3396472	Energy Cost (€/year)	1998676
TOTAL ANNUAL COST						
Equipment	*870647*					
Energy	*6049203*					
Total Cost	*6919850*					

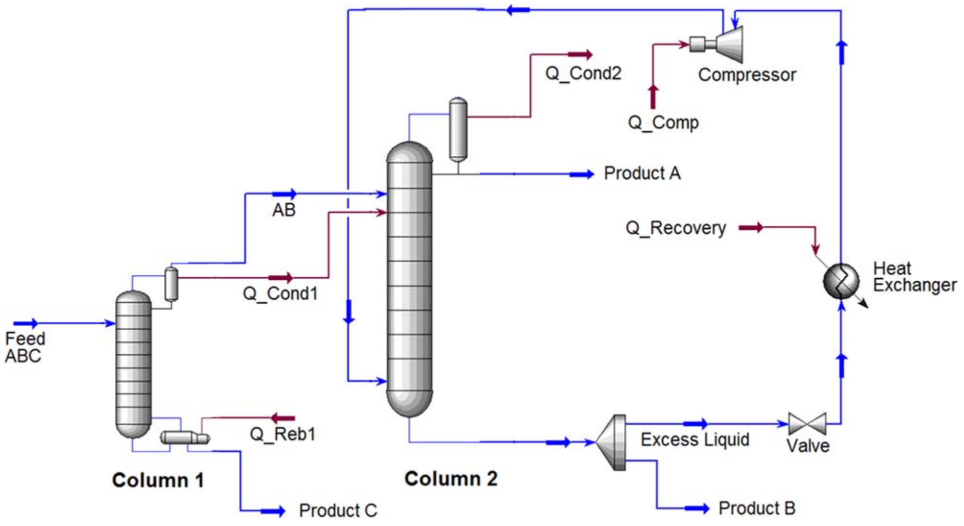

Figure 12. Simulation of indirect sequence with RVRC.

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

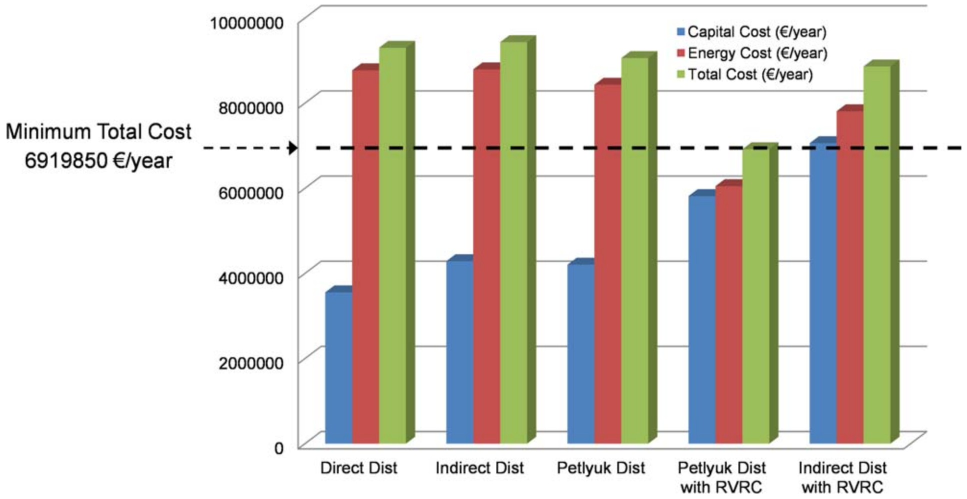

Figure 13. Annualized capital cost, energy costs and total costs for the distillation systems studied in example 2.

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

under some circumstances (i.e., divided wall columns) the investment costs are considerably reduced. Typical values of around 10 to 50% are frequently reported. However, even though FTC systems minimize energy consumption, in general we cannot be certain that they minimize total annual cost for two main reasons: The heat is added or removed under the worst conditions, at the maximum and minimum temperatures in the system; certain sections must be operated far away from their optimal conditions, in order to satisfy the mass balances introduced by thermal couples that increase some column section diameters and utilities consumption.

On the other hand, the large degree of integration—in a fully thermally coupled system it is possible to separate an N component mixture using only a condenser and a reboiler—prevent the installation of standard vapor recompression cycles because the temperature differences between condenser and reboiler are very large.

We have shown that it is possible to take advantage of the inherent inefficiency of TCD systems, by withdrawing the excess vapor (liquid) inside certain column sections and using it in a vapor recompression cycle (or a reverse vapor recompression cycle). The benefit is twofold; on one hand, the optimal operating conditions of the TCD system are recovered and therefore the diameter of some column sections and the utilities consumption are reduced. On the other, the VRC or RVRC allow further reductions in utilities consumption. In any case a detailed economic analysis is necessary because vapor recompression cycles entail using expensive equipment. However, the examples presented in this article show that economic savings can be very significant (20–40%).

It is clear that the new VRC cannot always be used. For example, consider the case of a three component mixture ABC. The most profitable situation occurs when the difference in volatilities between A and B are very small in comparison with the difference between B and C. (The reverse is true in the case of RVRC). Indeed, this volatility distribution causes both vapor and liquid flows between the coupled sections of the Petlyuk column to be very different.

As a general rule, the case of RVRC is only of interest if the condenser is working at subambient temperature (i.e., water cannot be used as cooling utility). Cooling with water is usually cheap and the extra cost of the compressor will likely make the RVRC suboptimal. However, refrigeration is expensive (usually much more so than heating), and in that case the economic incentive of a RVRC is larger than VRC.

Acknowledgments

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Appendix

Detailed Results of all Examples

The following tables contain the detailed results for all studied configurations (direct, indirect, Petlyuk distillation with and without VRC).

Results of example 1: Vapor recompression configuration

Table A1. Annual Capital Cost for all Configurations (€/year)

	CAPITAL COST					
	COLUMNS					
	Column 1			Column 2		
	V (m^3)	Cost (€)	Annualcost (€/year)	V (m^3)	Cost (€)	Annualcost (€/year)
DirectDist	201,6	728181	108520	205,0	754207	112399
IndirectDist	189,7	687087	102396	192,6	706815	105336
PetlyukDist	95,2	360010	53652	316,7	1136213	169329
PetlyukDistwith VRC	95,2	360010	53652	278,2	1002326	149376
IndirectDistwith VRC	201,6	728181	108520	192,6	706815	105336
	CONDENSER (Column 1)			REBOILER (Column 1)		
	A (m^2)	Cost (€)	Annualcost (€/year)	A (m^2)	Cost (€)	Annualcost (€/year)
DirectDist	189,0	119893	17868	–	–	–
IndirectDist	–	–	–	1109,4	326202	48614
PetlyukDist	–	–	–	–	–	–
PetlyukDistwith VRC	–	–	–	–	–	–
IndirectDistwith VRC	–	–	–	189,0	119694	17838
	CONDENSER (Column 2)			REBOILER (Column 2)		
	A (m^2)	Cost (€)	Annualcost (€/year)	A (m^2)	Cost (€)	Annualcost (€/year)
DirectDist	101,4	93491	13933	1738,5	451580	67299
IndirectDist	300,8	149166	22230	293,3	147277	21949
PetlyukDist	222,1	128757	19189	1273,1	359296	53546
PetlyukDistwith VRC	183,1	127125	18945	1042,5	336634	50168
IndirectDistwith VRC	1047,3	313532	46726	–	–	–
	HEATER			COOLER		
	A (m^2)	Cost (€)	Annualcost (€/year)	Energ (kw)	Cost (€)	Annualcost (€/year)
DirectDist	–	–	–	–	–	–
IndirectDist	–	–	–	–	–	–
PetlyukDist	–	–	–	–	–	–
PetlyukDistwith VRC	10,0	15862	2364	7,6	15051	2243
IndirectDistwith VRC	27,4	66558	9919	23,0	64784	9655
	HEAT EXCHANGER			COMPRESSOR		
	A (m^2)	Cost (€)	Annualcost (€/year)	Energ (kw)	Cost (€)	Annualcost (€/year)
DirectDist	–	–	–	–	–	–
IndirectDist	–	–	–	–	–	–
PetlyukDist	–	–	–	–	–	–
PetlyukDistwith VRC	534,0	219997	32786	144,8	151439	22569
IndirectDistwith VRC	1680,6	440206	65604	438,4	395890	58999

Table A2. Annual Energy Cost for all Studied Configurations (€/year)

	ENERGY COST					
	CONDENSER (Column 1)			REBOILER (Column 1)		
	Energy (kw)	Utility	Annualcost (€/year)	Energy (kw)	Utility	Annualcost (€/year)
DirectDist	7465,1	Water	75982	–	–	–
IndirectDist	–	–	–	7690,6	Med Pres Steam	1817633
PetlyukDist	–	–	–	–	–	–
PetlyukDistwith VRC	–	–	–	–	–	–
IndirectDistwith VRC	–	–	–	7260,3	Med Pres Steam	1715935
	CONDENSER (Column 2)			REBOILER (Column 2)		
	Energy (kw)	Utility	Annualcost (€/year)	Energy (kw)	Utility	Annualcost (€/year)
DirectDist	4543,6	Water	46246	12051,8	Med Pres Steam	2848379
IndirectDist	11878,1	Water	120899	4212,2	Med Pres Steam	995522
PetlyukDist	8772,0	Water	89284	8825,7	Med Pres Steam	2085902
PetlyukDistwith VRC	7230,6	Water	73595	7227,1	Med Pres Steam	1708072
IndirectDistwith VRC	7465,1	Water	75982	–	–	–
	HEATER			COOLER		
	Energy (kw)	Utility	Annualcost (€/year)	Energy (kw)	Utility	Annualcost (€/year)
DirectDist	–	–	–	–	–	–
IndirectDist	–	–	–	–	–	–
PetlyukDist	–	–	–	–	–	–
PetlyukDistwith VRC	298,5	High Pres Steam	84378	338,1	Water	3441
IndirectDistwith VRC	832,6	High Pres Steam	235314	1030,9	Water	10493
	COMPRESSOR					
	Energy (kw)	Utility	Annualcost (€/year)			
DirectDist	–	–	–			
IndirectDist	–	–	–			
PetlyukDist	–	–	–			
PetlyukDistwith VRC	144,8	Electricity	69368			
IndirectDistwith VRC	438,4	Electricity	210097			

Table A3. Total Annual Cost for all Studied Configurations (€/year)

	TOTAL COST		
	Capital Cost (€/year)	EnergyCost (€/year)	Total AnnualCost (€/year)
DirectDist	320019	2970608	3290627
IndirectDist	300525	2934054	3234579
PetlyukDist	295716	2175186	2470901
PetlyukDistwith VRC	**332104**	**1938855**	**2270959**
IndirectDistwith VRC	422597	2247821	2670418

Results of example 2: The reverse vapor recompression configuration

Table A4. Annual Capital Cost for all Configurations (€/year)

	CAPITAL COST					
	COLUMNS					
	Column 1			Column 2		
	V (m^3)	Cost (€)	Annualcost (€/year)	V (m^3)	Cost (€)	Annualcost (€/year)
DirectDist	199,3	1733135	258288	72,8	835298	124484
IndirectDist	68,0	732040	109096	268,7	2490896	371217
PetlyukDist	49,6	521794	77763	287,4	2941774	438411
PetlyukDistwith RVRC	49,6	521794	77763	257,7	2354008	350817
IndirectDistwith RVRC	68,0	732040	109096	261,0	2686405	400354
	CONDENSER (Column 1)			REBOILER (Column 1)		
	A (m^2)	Cost (€)	Annualcost (€/year)	A (m^2)	Cost (€)	Annualcost (€/year)
DirectDist	1546,6	419777	62559	–	–	–
IndirectDist	–	–	–	586,6	219153	32660
PetlyukDist	–	–	–	–	–	–
PetlyukDistwith RVRC	–	–	–	–	–	–
IndirectDistwith RVRC	–	–	–	588,3	219530	32716
	CONDENSER (Column 2)			REBOILER (Column 2)		
	A (m^2)	Cost (€)	Annualcost (€/year)	A (m^2)	Cost (€)	Annualcost (€/year)
DirectDist	912,4	289843	43195	847,2	276035	41137
IndirectDist	2215,5	552593	82353	921,8	291827	43491
PetlyukDist	1804,0	471174	70219	817,1	269591	40177
PetlyukDistwith RVRC	1168,5	343114	51134	512,7	202340	30155
IndirectDistwith RVRC	1623,5	435186	64856	–	–	–
	HEAT EXCHANGER			COMPRESSOR		
	A (m^2)	Cost (€)	Annualcost (€/year)	Energ (kw)	Cost (€)	Annualcost (€/year)
DirectDist	–	–	–	–	–	–
IndirectDist	–	–	–	–	–	–
PetlyukDist	–	–	–	–	–	–
PetlyukDistwith RVRC	6844,1	1474823	219792	1364,9	946032	140987
IndirectDistwith RVRC	8886,3	1899397	283066	1658,5	1085927	161835

Table A5. Annual Energy Cost for all Studied Configurations (€/year)

	ENERGY COST					
	CONDENSER (Column 1)			REBOILER (Column 1)		
	Energy (kw)	Utility	Annualcost (€/year)	Energy (kw)	Utility	Annualcost (€/year)
DirectDist	11945,6	VeryLowTemp	4502819	–	–	–
IndirectDist	–	–	–	11920,2	Atm Steam	2286026
PetlyukDist	–	–	–	–	–	–
PetlyukDistwith RVRC	–	–	–	–	–	–
IndirectDistwith RVRC	–	–	–	11954,3	Atm Steam	2292561
	CONDENSER (Column 2)			REBOILER (Column 2)		
	Energy (kw)	Utility	Annualcost (€/year)	Energy (kw)	Utility	Annualcost (€/year)
DirectDist	4257,6	LowTemp	965855	17213,4	Atm Steam	3301154
IndirectDist	17092,4	VeryLowTemp	6442843	6261,8	Water	63735
PetlyukDist	13940,5	VeryLowTemp	5254756	16561,6	Atm Steam	3176150
PetlyukDistwith RVRC	9010,6	VeryLowTemp	3396472	10421,8	Atm Steam	1998676
IndirectDistwith RVRC	12525,0	VeryLowTemp	4721212	–	–	–
	COMPRESSOR					
	Energy (kw)	Utility	Annualcost (€/year)			
DirectDist	–	–	–			
IndirectDist	–	–	–			
PetlyukDist	–	–	–			
PetlyukDistwith RVRC	1364,9	Electricity	654055			
IndirectDistwith RVRC	1658,5	Electricity	794768			

Table A6. Total Annual Cost for all Studied Configurations (€/year)

	TOTAL COST		
	Capital Cost (€/year)	EnergyCost (€/year)	Total AnnualCost (€/year)
DirectDist	529664	8769829	9299493
IndirectDist	638816	8792604	9431420
PetlyukDist	626570	8430906	9057476
PetlyukDistwith RVRC	**870647**	**6049203**	**6919850**
IndirectDistwith RVRC	1051922	7808540	8860463

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