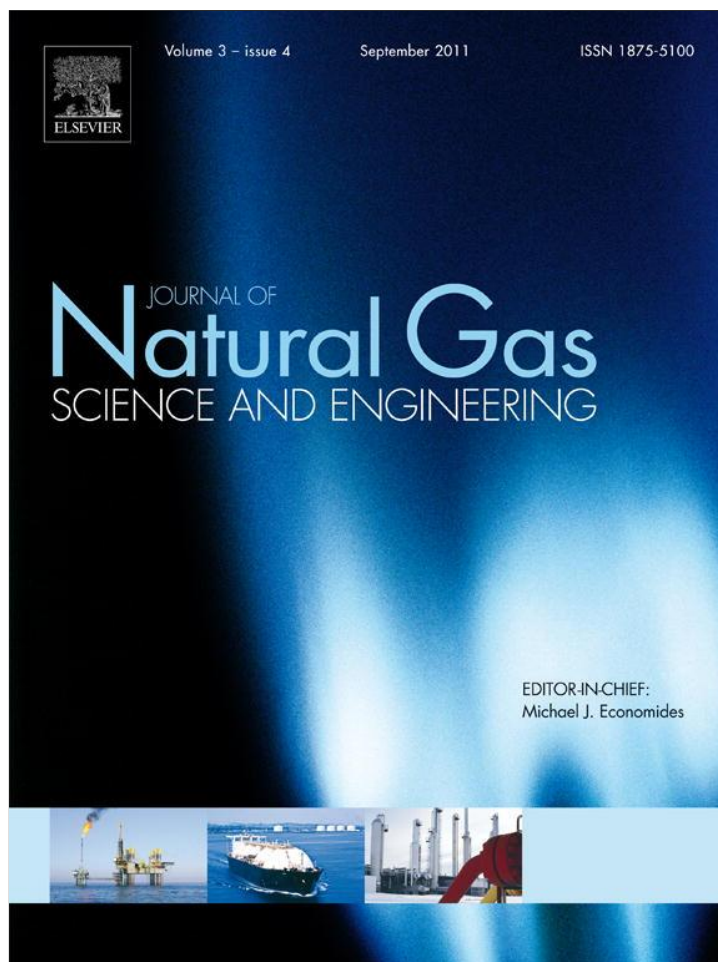


Provided for non-commercial research and education use.  
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

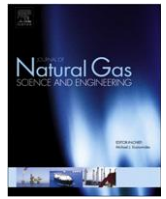
In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at ScienceDirect

## Journal of Natural Gas Science and Engineering

journal homepage: [www.elsevier.com/locate/jngse](http://www.elsevier.com/locate/jngse)

## Energy efficient distillation

Ivar J. Halvorsen<sup>a,\*</sup>, Sigurd Skogestad<sup>b</sup><sup>a</sup> SINTEF ICT, Applied Cybernetics, O.S. Bragstads plass 2D, 7465 Trondheim, Norway<sup>b</sup> Norwegian University of Science and Technology (NTNU), Department of Chemical Engineering, 7492 Trondheim, Norway

## ARTICLE INFO

## Article history:

Received 5 March 2010

Received in revised form

1 November 2010

Accepted 8 June 2011

Available online 16 July 2011

## Keywords:

Distillation

Minimum energy

Energy saving

Dividing wall column

Petlyuk arrangement

Vmin-diagram

## ABSTRACT

Distillation is responsible for a significant amount of the energy consumption of the world's process industry and also in the natural gas processing. There is a significant energy saving potential that can be obtained by applying new energy saving distillation technology that has appeared in the last two decades. The fully thermally coupled dividing wall columns have the attractive feature of both savings in energy consumption and reduction of investment cost. In this paper we give an overview of some energy saving distillation arrangements and show how the Vmin-diagram can be used to assess separations and calculate energy requirements and provide a basis for detailed design. Reduced CO<sub>2</sub> emission is an additional benefit that actually comes for free by the reduction of energy consumption.

© 2011 Elsevier B.V. All rights reserved.

## 1. Introduction

New distillation arrangements, like the dividing wall columns (DWC) (Kaibel, 1987), internally heat integrated columns (HIDiC) (Nakaiwa et al., 2003), heat integrated double and multi-effect columns show that there is a potential for significant reduction of energy consumption in distillation.

The separation of a feed mixture into a set of product streams is a basic task in natural gas processing. The objective is to obtain products that are sufficiently pure for further usage and conversion, and to carry out this separation with a minimum cost and energy consumption. Distillation is the most widely used industrial separation technology and distillation units consume a significant part of the total heating energy in the world's process industry. Distillation has been in use for a very long time and is often regarded as mature technology. However, demands to reduce capital costs, energy consumption and operation and maintenance costs, has lead to rethinking how the separation should be carried out. As CO<sub>2</sub> emissions are directly related to the energy consumption, more energy efficient distillation also contribute directly to reduction in CO<sub>2</sub> emissions. In addition, more energy efficient configurations

that reduce the internal vapour and liquid flow rates give more compact units with a smaller diameter and thus reduce the capital cost (Agrawal, 2001).

The dividing wall column is an implementation of the fully thermally coupled Petlyuk column arrangement (Petlyuk et al., 1965) in a single shell. All these new arrangements aim at making the column operate closer to the ideal reversible system by reducing the thermodynamic losses. However, whereas the HIDiC approach with internal heat exchange between sections focuses on increasing the efficiency of a single binary distillation column, the Petlyuk (fully thermally coupled) arrangements and multi-effect columns are used for multicomponent separations.

We will illustrate some energy saving distillation arrangements and present how minimum energy requirements and detailed internal flow distribution can be calculated for fully thermally coupled arrangements. The solution is amazingly simple, as the minimum energy for a complex integrated extended Petlyuk arrangement is given by the most difficult of the product splits if that split is performed in a single two-product column.

In addition, external heat integration with other units in a plant is an option to save energy and reduce thermodynamic losses. A particular plant may have available heat sources and heat consumers at various temperature levels that may be utilised in conjunction with distillation units (Smith, 2005). However, this paper focuses on the energy efficiency within the distillation arrangements, and on multicomponent separation.

\* Corresponding author. Tel.: +47 73594387; fax: +47 73594399.

E-mail addresses: [Ivar.J.Halvorsen@sintef.no](mailto:Ivar.J.Halvorsen@sintef.no) (I.J. Halvorsen), [skoge@ntnu.no](mailto:skoge@ntnu.no) (S. Skogestad).

The number of installed Dividing Wall Columns has passed one hundred (2009) and covers a range of different applications and sizes. A comprehensive overview of applications and engineering development is given by Dejanovic et. al. (Dejanović et al., 2010). Most of these are three-product columns but also some four-product columns have now been built: The largest at present has a diameter of 4 m (Olujic et al., 2009). A very attractive feature of the DWC is that in addition to save energy, it also saves capital cost and installation space. There are also revamp examples (Kolbe and Wenzel, 2004) resulting in both higher purity, higher throughput and less energy consumption compared to the original conventional arrangement. Many of the installed DWCs are in the chemical industry where energy usage is not a main concern, so the main reason for using Petlyuk columns is to simplify the design and save capital costs (Kaibel et al., 2004; Parkinson, 2007).

In this paper, we want to emphasize the potential energy savings (Halvorsen, 2001; Halvorsen and Skogestad, 2003a), where one main concern is good operation and control (Wolff and Skogestad, 1995; Halvorsen and Skogestad, 1999a). The typical potential energy savings for a three-product Petlyuk arrangement are in the range 20–30% (Triantafyllou and Smith, 1992). However, more complex fully thermally coupled arrangements have even larger potential, and an analysis of typical petroleum crude distillation towers shows a potential reduced vapour flow of 48% for a light crude by applying fully thermally coupled sections (Shah and Agrawal, 2009).

## 2. Background theory

### 2.1. Entropy and minimum energy

There is “no free lunch” with regards to separation. Thermodynamic work has to be provided to facilitate the increase in the entropy of mixing the streams ( $\Delta S$ ). Distillation is a thermal separation process, where separation work is supplied by adding heat ( $Q$ ) at high temperature  $T_H$  in the reboiler and removing about the same amount of heat ( $Q$ ) at low temperature  $T_C$  in the condenser. The theoretical minimum heat supply for a reversible process operating under these conditions is given by:

$$Q_{\min} = \frac{\Delta S T_C}{1 - \frac{T_C}{T_H}} \quad (1)$$

Here, the entropy change for ideal mixing of pure components is given by:

$$\Delta S = -R \sum x_i \ln(x_i) \quad (2)$$

Here  $x$  denotes the molar fraction of component  $i$  and  $R$  is the universal gas constant.

The energy usage  $Q$  in conventional distillation arrangements is typically more than 50% higher than  $Q_{\min}$  due to inevitable entropy losses, in particular due to remixing within column sections and interconnections and temperature differences in heat exchangers (reboiler and condenser).

Ideally, we want both a low energy consumption  $Q$  (ref. 1st law of thermodynamics) and a high thermodynamic efficiency  $Q_{\min}/Q$  corresponding to a small entropy loss (2nd law). In practise, this is in a way translated to a balance of capital cost (CAPEX) an operating cost (OPEX) as thermodynamic ideal configurations tend to require larger columns and heat exchanger areas.

Observe that  $Q_{\min}$  is not fixed, but depends heavily on the temperature span,  $T_H - T_C$ . Thus, if we change the process to work across a larger span and we observe that the required heat flow  $Q$  is

reduced (improved 1st law efficiency), then the thermodynamic efficiency may not be improved after all because  $Q_{\min}$  has also decreased (so 2nd law efficiency may not improve). Thus, we have to check the entropy production against the ideal reversible process at the actual temperature spans. However, to turn the case around, if we have available heat at a certain temperature, e.g. from a reactor, and have cooling available at another low temperature, then we should design the distillation arrangement to utilize the given temperature span.

### 2.2. Reversible distillation

It is possible to devise a theoretical, reversible distillation column. Grunberg (1956), Petlyuk et al. (1964) and Fonyo (1974) give a basic description of both a binary column in Fig. 1 and a multicomponent arrangements. To get the minimum energy for distillation, we assume an infinite number of stages.

The key to the binary reversible column is to supply heat along the stripping section and to remove heat along the rectifying section in order to obtain the local operating line parallel to the equilibrium curve. An interesting observation is that the required vapour flow across the feed stage will have to be exactly the same as for ordinary columns (Halvorsen, 2001). A reversible multicomponent arrangement can be made by fully thermally coupled reversible sub-columns as shown in Fig. 2 for a ternary feed. Fully thermally coupled arrangements are described closer in section 3.2.

In multicomponent distillation, Petlyuk (F.B.a.P. Petlyuk and Slavinskii, 1965) and Fonyó (Fonyo, 1974) list two main properties that limit the possibilities for reversible operation:

1. Only one component can be removed in each end of a 2-product column. This is due to the fact that a pinch zone is needed across the feed stage, and this is only possible for so-called Class 1 separations. If we relate this to the  $V_{\min}$ -diagram (see below), reversible operation is only possible at

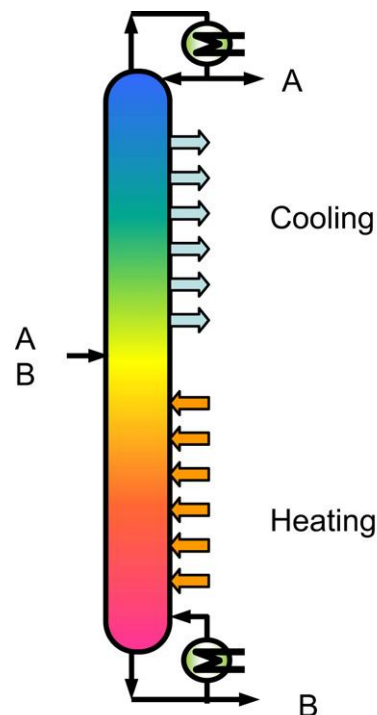


Fig. 1. A reversible binary distillation column has heat supply along the stripping section and cooling along the rectifying section.

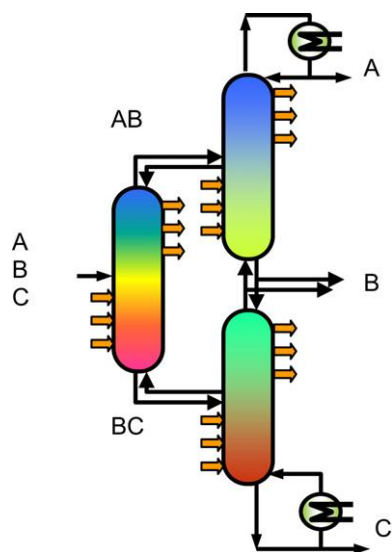


Fig. 2. The fully reversible Petlyuk arrangement for separation of three components.

the preferred split, where we remove exactly one feed component in each end.

2. The top reflux must be in equilibrium with the vapour flow leaving. This is not possible for other than a binary mixture with an ordinary condenser unless the liquid flow rate is zero. There is a similar relation for the bottom flows.

Note that both these limitations are overcome with a Petlyuk arrangement: Only one component at a time is removed in each sub-column and we have reversible mixing in all junctions when it is operated properly. This is the main explanation for the energy saving capability, but heating and cooling along the sections would be required for the full reversible system.

Note that the two conditions imply that if we have more than two components in the feed, a two-product column as shown in Fig. 1 cannot be made completely reversible even if we are able to supply or remove arbitrary amounts of heat along the column.

### 3. Arrangements for multicomponent separation

#### 3.1. Conventional column sequence (reference)

A typical reference is the direct- and indirect split sequences of two-product columns as shown in Fig. 3.

Note that each column produces a pure product in one end, and the product mixture at the other end is fed to a succeeding column.

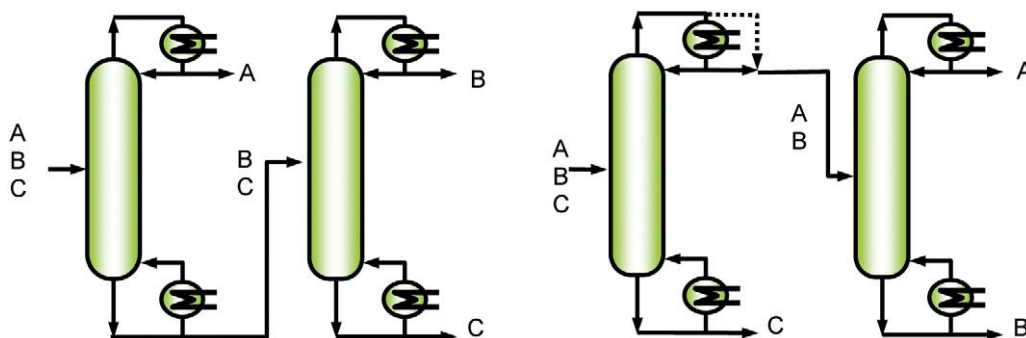


Fig. 3. Conventional direct- (left) and indirect (right) split arrangement for separating a three-component mixture (ABC).

The feed to the succeeding column may also be vapour as indicated by the dashed line. Another approach is the prefractionator arrangement as shown in Fig. 4.

The prefractionator produces no final product, but instead performs the sloppy A/C split, while the intermediate B-component is distributed to both ends. The final purification is performed in the succeeding columns. An interesting approach is shown to the right where reboiler and condenser handling the pure B-product are simply removed and the two columns can be in the same shell. Now, the bottom reboiler must supply the maximum of either the A/B or the B/C split required in the two-product columns.

#### 3.2. Fully thermally coupled Petlyuk arrangements

Fully thermally coupled arrangements, also called Petlyuk arrangements (F.B.a.P. Petlyuk and Slavinskii, 1965), may reduce internal vapour flow rates, and thereby the need for external heating and cooling. A promising implementation of this is the dividing wall column (DWC) (Kaibel, 1987). The three-product DWC replaces the two conventional columns shown in Fig. 3 with one single column shell as shown in Fig. 5b. The arrangements in Fig. 5 are thermodynamically equivalent. In the dividing wall column, the prefractionator is moved into the same shell and is simply separated by the dividing wall. The basis for the configuration is the prefractionator arrangement in Fig. 4, but now also the reboiler and condenser of the prefractionator column is removed and replaced with directly connected vapour and liquid streams. This is called full thermal coupling. The term may be a bit confusing since there is no heat exchange involved. When this system is properly operated, the potential energy savings are 20–40% compared to the conventional structures, dependant on feed composition, relative volatility and product purity specifications. The energy savings are due to reduced mixing loss at the interconnections, since the vapour and liquid streams will be in equilibrium when properly operated. In addition, the compactness of the DWC arrangement as well as reduced internal flow rates gives reduced equipment size also give capital savings as an extra benefit (Olujić et al., 2009). This is a very attractive feature with the DWC, since it very often is a trade-off between reducing operating cost at the expense of higher investment costs. But with the DWC we get both benefits at the same time (Dejanović et al., 2010).

For four-product separation the potential energy savings are even higher. An interesting configuration is the Kaibel-arrangement (Kaibel, 1987) as shown in Fig. 6. The prefractionator now does the sharp AB/CD split.

The four-product Kaibel column is very attractive due to its simple construction. It actually replaces three conventional two-product columns in direct/indirect split sequences. For a saturated liquid feed with relative volatilities 6:4:2:1 the potential

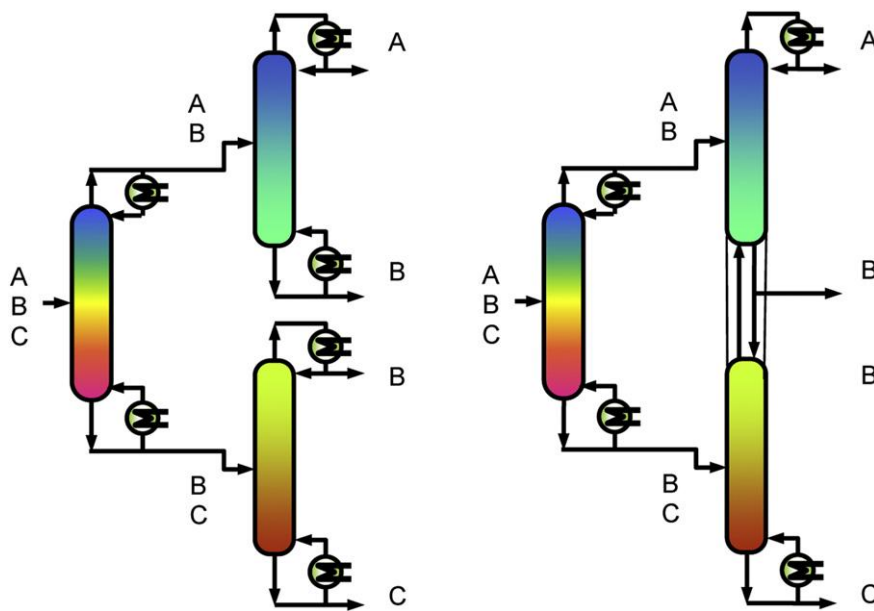


Fig. 4. Prefractionator arrangements.

savings can be shown to be 33% compared to a direct split sequence of three conventional columns (Halvorsen and Skogestad, 2006). Even if the sections are fully thermally coupled, separation of two components at once violates one of the conditions of the ideal reversible distillation column, and introduce some irreversibility.

However, even greater savings can be obtained if we consider the extended Petlyuk arrangement as shown in Fig. 7. The key property of the extended Petlyuk arrangement is that each sub-column only removes the heavy key in the top and the light key in the bottom while all intermediates distribute. Then the first condition of the reversible column is fulfilled. The equilibrium condition is fulfilled by operating each sub-column at its local preferred split. The figure shows the case with four products, but in theory we can extend this structure to any number of products. For  $N$  products  $N-1$  rows of sub-columns are needed.

The potential savings can now approach 40–50% (Halvorsen and Skogestad, 2006). This implies also that the full Petlyuk DWC in Fig. 7 requires a smaller column diameter, and smaller reboiler and condenser than the corresponding DWC column in Fig. 6. However, the internals with the multiple partition walls makes the full Petlyuk DWC somewhat more complex, but still feasible and even with a bit higher capital cost the higher energy savings makes it attractive (Dejanović et al., 2011).

#### 4. Minimum energy calculations

In order to quantify the energy consumption we use the concept of minimum energy or minimum vapour flow rate ( $V_{min}$ ) where we assume sections with infinite number of stages. Thus, these numbers will be independent of the detailed stage design. In practise, the real number of stages is selected based on the required separation purity and balancing CAPEX (equipment cost) and OPEX (energy cost), and the real energy input will be slightly higher than the minimum requirements. However,  $V_{min}$  is a straightforward and common measure used to compare the energy consumption in different distillation arrangements.

##### 4.1. The $V_{min}$ -diagram

We will here describe the  $V_{min}$ -diagram, or minimum energy diagram, and how it can be used for assessment of multicomponent separations. We first consider a single two-product column with a multicomponent feed ( $F$ ). The minimum energy requirement for a given product specification is indirectly determined by the minimum vapour flow through the feed stage in a column with an infinite number of stages. The equivalent heat flow to generate this vapour flow can be obtained by multiplying with the heat of vapourisation. We consider the case with constant pressure. Then we have at steady state two degrees of freedom in operation. We select to use the vapour flow rate above the feed ( $V/F$ ) and the net flow of product to the top ( $D/F$ ) per unit feed. For each given pair ( $D/F$ ,  $V/F$ ) all other properties are completely determined, such as all component recoveries and product compositions. The feed enthalpy condition is given by the liquid fraction ( $q$ ).

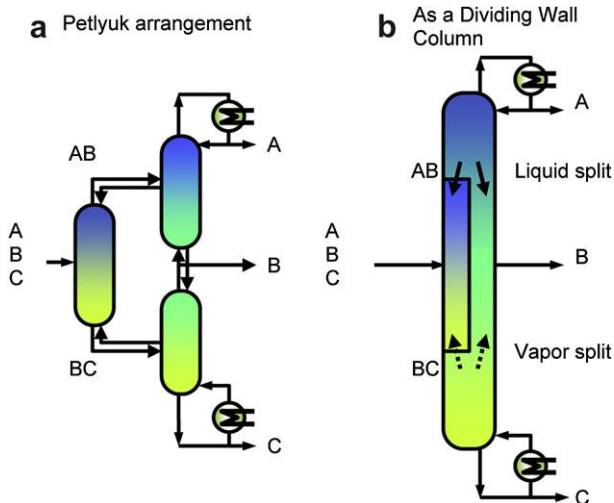


Fig. 5. The fully thermally coupled (Petlyuk) arrangement (a) replaces the conventional arrangements with a prefractionator and a main column, and only a single reboiler and a single condenser is needed. By moving the prefractionator into the same shell we obtain the Dividing Wall Configuration (b).

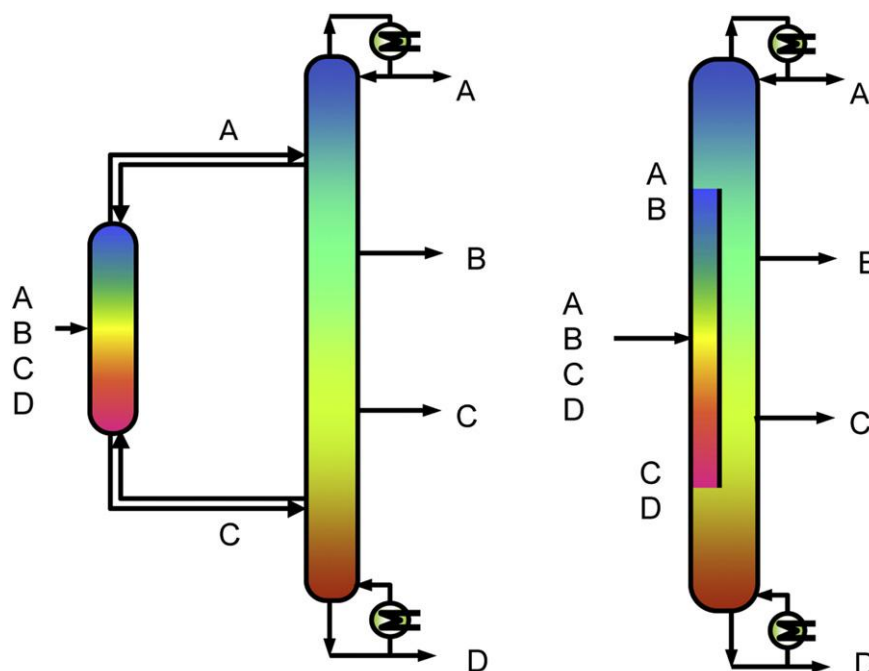


Fig. 6. Four-product prefractionator arrangement (left) and DWC-Kaibel-column (right).

The  $V_{min}$ -diagram in Fig. 8 shows how the feed components for a ternary feed (ABC) are distributed to the top and bottom products in a simple two-product “infinite stage” distillation column as a function of the operating point ( $D/F, V/F$ ). For values of  $V/F$  above the upper “mountain-like” boundary in the diagram ( $[0,0]-P_{AB}-P_{AC}-P_{BC}-[1,1-q]$ ), the column is over-fractionated, that is, we are wasting energy. The values at the peaks give vapour flow  $V_{min}$  for the corresponding sharp neighbour component splits. As the vapour flow  $V$  is reduced below the line for a given  $D$ , one more component will become distributed as we cross boundary lines. The knots (bottom of the valleys) are  $V_{min}$  for the so-called “preferred splits” where we specify sharp split between two key-components, while we allow intermediate components being distributed. To find the diagram for a multicomponent feed, we only need to solve for sharp split between each possible pair of key-components. That is, for  $n$  components ( $n > 1$ ), we can find the complete diagram by calculating  $1+2+3+\dots+n-1 = n(n-1)/2$  points. For the three-component example we only need three points:  $P_{AB}$ : sharp A/B,  $P_{BC}$ : sharp B/C and  $P_{AC}$ : sharp A/C.  $P_{AC}$  is the “preferred split” (Stichlmair, 1988) which is the minimum energy operating point for a sharp separation between the heavy and light keys while the intermediate distribute to both column ends. At any operating point at or above the V-shaped  $P_{AB}-P_{AC}-P_{BC}$  we also get a sharp A/C split, but with higher energy than exactly at  $P_{AC}$ .

The diagram for real mixtures may simply be obtained by simulating the given multicomponent feed in a two-product column with a large number of stages. The simulation is carried out for different values of the product split ( $D/F$ ) one computes the corresponding  $V_{min}/F$  to get the specified high-purity (or desired purity) product. The term  $V_{min}$  means that it is the minimum  $V$  corresponding to an infinite number of stages, but in practise one may get very close to  $V_{min}$  with a finite number of stages, typically  $N=4N$ . Also note that in distillation, the value of  $V_{min}$  depends only weakly on the purity for high-purity separations. Thus, in practise we may specify small impurities of heavy key in the top and light in the bottom for each pair of keys. In the case of a binary feed, there will be only one peak.

For ideal mixtures with constant relative volatility and constant molar flows one can obtain the  $V_{min}$ -diagram without the need to do time consuming simulations. Here, for an infinite number of stages, one may use the classical Underwood equations and the  $V_{min}$ -diagram can be calculated directly from the feed properties (Halvorsen and Skogestad, 2003b). Fig. 9 shows the  $V_{min}$ -diagram for a 5-component feed mixture. Note that the boundaries for different recoveries are linear in each region, and so is any contour line for a constant recovery value.

#### 4.2. Minimum energy for Petlyuk arrangements

The real power of the  $V_{min}$ -diagram is that it contains all necessary information to calculate the overall minimum energy

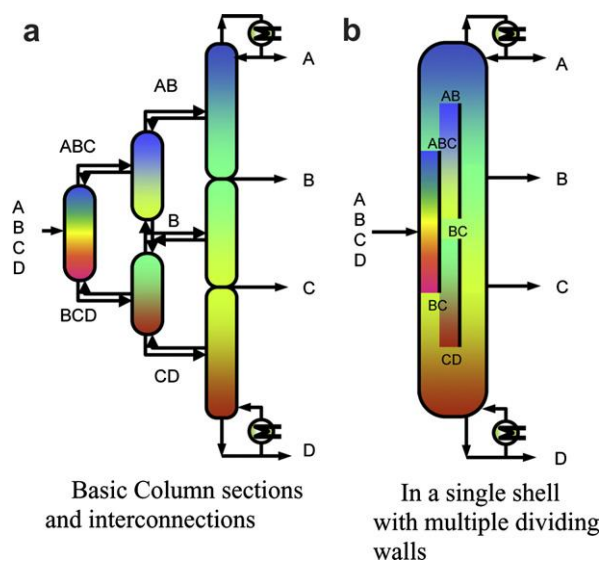


Fig. 7. Extended Petlyuk arrangements to four products.

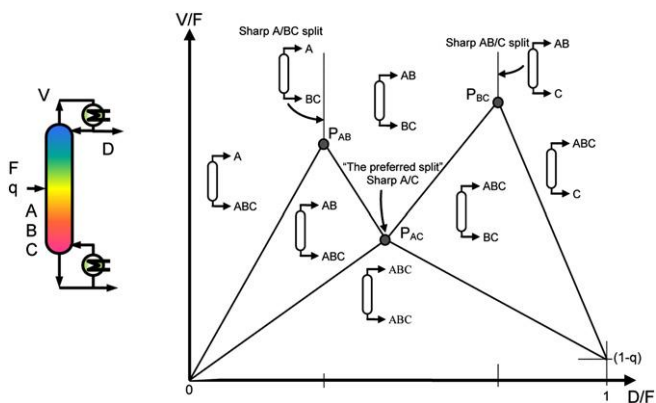


Fig. 8. The Vmin-diagram for a ternary feed.

requirement and all the internal flow rates for an optimally operated extended Petlyuk arrangement for an arbitrary multicomponent feed and any number of products. This is the main result by Halvorsen (2001) (Halvorsen and Skogestad, 2003a; Halvorsen and Skogestad, 2003c). The overall minimum energy is simply given by the highest peak. This peak represents the most difficult product split in a two-product column. It may be a bit surprising that by supplying this vapour rate to an extended Petlyuk arrangement we get all the other products separated for “free”. The key is that in an optimal operated Petlyuk arrangement, each sub-column in the structure must be operated at its local “preferred split”. That is, at minimum energy for separation of the light and heavy keys for that column while the intermediates distribute to both ends. We would generally anticipate that we would need to calculate the minimum energy for each succeeding column by a new column computation, but Halvorsen showed that the properties determining minimum energy in each sub-column can be found from the previous column, and at optimal operation in the sequence, all the information can be obtained from the Vmin-diagram which is based on feed data only. It is also shown that an optimally operated generalized Petlyuk arrangement results in the lowest overall vapour flow requirement for any distillation

configuration when we consider constant pressure and no external heat integration.

In general, the main use of the Vmin-diagram is a graphic tool which can be generated by simulation of any mixture. Additionally, for ideal mixtures with constant relative volatility and constant molar flows, there is also a set of analytical functions that can be used to obtain exact values for recoveries and flows for any operating point and feasible combination of two specifications. For example: Two components recoveries, one recovery and one flow, two compositions, and of course one vapour and one distillate flow rate. By calculating the flow requirements for each sub-column and inspecting the mass balances at each junction, we can find all the internal streams in the extended 4-product Petlyuk arrangement shown in Fig. 2. However, it is much easier to show the relationship graphically in the Vmin-diagram. Each section’s vapour flow and net top product flow can be found directly as a difference between the peaks and knots in the Vmin-diagram. We show this for a 4-component feed in Fig. 10 (Superscripts denote sub-columns, and the subscripts T and B denote the top or bottom section in that sub-column). The liquid flow rates and bottom net flows are uniquely determined from simple mass balances.

Note that when the peaks are of different height, one may in order to improve the thermodynamic (2nd law) efficiency apply heat exchange at each side-stream stage and condense or vaporize an amount of vapour/liquid representing the difference in the height of the peaks. However, this increases the complexity and as it not common in industrial applications with DWC columns. Instead, the vapour flow corresponding to the highest peak is normally supplied in the reboiler and passes through the whole column. The splits corresponding to the other peaks will then be done with higher vapour rate than actually required. This gives a certain slack in the operation which may be beneficial, since each sub-column does not have to be operated exactly at its local preferred split. We only have to make sure that we operate in a way that does not increase the minimum vapour for the most difficult split (the highest peak). We will not go into the details here, but this is the reason for the “flat” optimality region (Christiansen et al., 1997) that enables a DWC to operate optimally and handle feed property variations even with a fixed vapour split. However, the optimality region is still limited and suboptimal operation is characterized with higher energy consumption for a given product specification, or that the column is unable to produce the required product purities for the given heat supply.

4.3. A simple revamp case: butane separation

We will illustrate the use of the Vmin-diagram on a simple example: Consider an arrangement for separation of i-butane (A), n-butane (B), i-pentane and heavier (C) which is a typical separation task in a wet gas separation train. A conventional solution is to first separate out the heavier components in the bottom of a standard column and then separate the top product consisting of i-butane and n-butane in a succeeding column in a standard indirect split configuration as shown in Fig. 3. The Vmin-diagram with feed data is shown in Fig. 11.

The sum of the boilup rates per unit feed for the two conventional columns are found as  $V/F = 3.24$ , where the boilup in the first column is 1.19 and 2.04 in the butane splitter. Based on the Vmin-diagram, we observe the highest peak at 2.12, and this will be the boilup requirement in a Petlyuk arrangement or a dividing wall column as shown in Fig. 5. This gives a total saving of above 30%. Note that the requirement of vapour flow in the prefractionator is given by the preferred split which is at  $V/F = 0.86$ .

However, observe that there is a considerable difference in the vapour flow required to separate A/B compared to B/C. Thus, it is

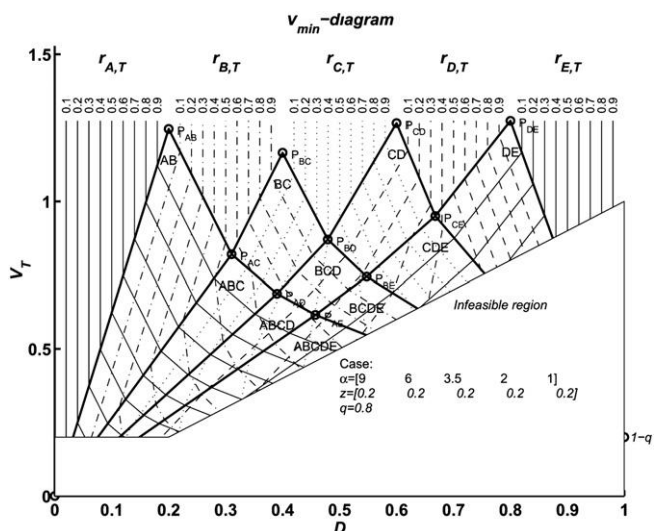


Fig. 9. A Vmin-diagram for a 5-component feed mixture. Contours for individual component (ABCDE) recoveries in the top of a two-product column show the detailed distribution.

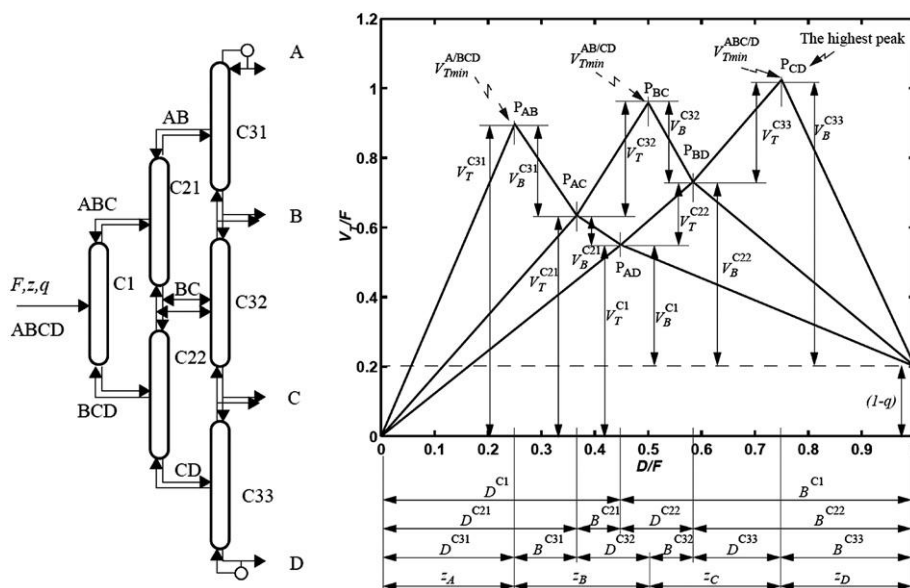


Fig. 10. The extended 4-product Petlyuk arrangement and a  $V_{min}$ -diagram for a 4-component feed with indication of how to calculate the individual vapour rates in all sub-columns.

only needed to supply the heat required for B/C in the reboiler of the Petlyuk arrangement, but the rest must be supplied at or below the side-stream stage. This actually gives the opportunity to reuse the original column shells. As an example we may modify the conventional indirect split (ISV) from Fig. 3 into the fully thermally coupled arrangement shown in Fig. 12. The first column may be operated at a higher pressure giving us the possibility to control both connecting vapour flows (Agrawal, 1999). The lower valve affects the vapour split, giving one more degree of freedom compared to a DWC where the vapour split normally is set by the design. The first reboiler now runs with the same heat duty as the conventional arrangement. The prefractionator can be regarded as the upper part of the first column, down to the junction point. The lower right sub-column of the general Petlyuk arrangement in Fig. 5 is divided in two parts with the stripping section in the bottom of the first column, and the rectifying section in the bottom of the butane splitter. Note that the n-butane product outlet is not in the bottom, but somewhere in the stripping section of the

original butane splitter. The duty of the new butane splitter reboiler is only 0.93 (original 2.05), and is given by the difference in height of the peaks in the  $V_{min}$ -diagram. The condenser of the original first column is removed.

This example shows that we can calculate the potential savings by applying full thermal coupling. We also show that reuse existing columns are possible and that there are several options for column connections and placement of sections within shells.

### 5. Control

In control of distillation columns, the most important issue is to avoid drift in the column by stabilising the column profile (Skogestad, 2007). In two-product columns it is common to do this by manipulate e.g. reflux to maintain a certain temperature somewhere between the feed stage and product stage. The sufficient purity in both products is obtained if we ensure a large enough energy input for the given feed rate. This mode of operation

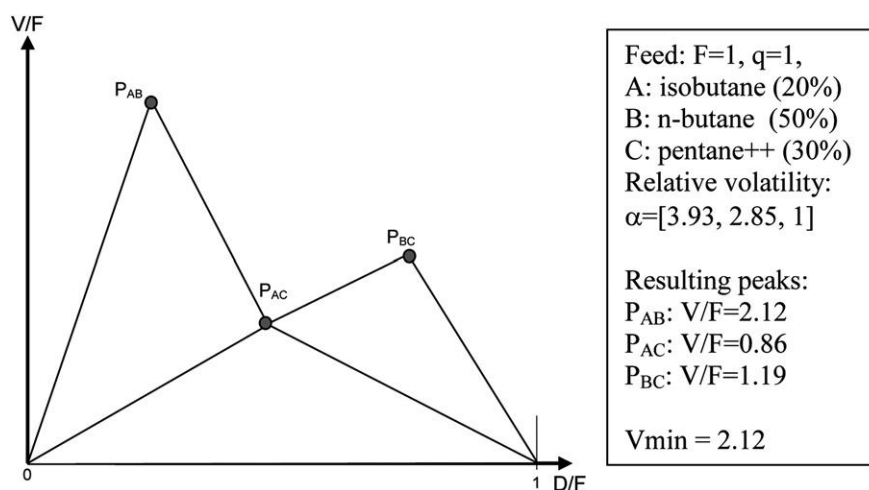


Fig. 11. The  $V_{min}$ -diagram for the butane separation.



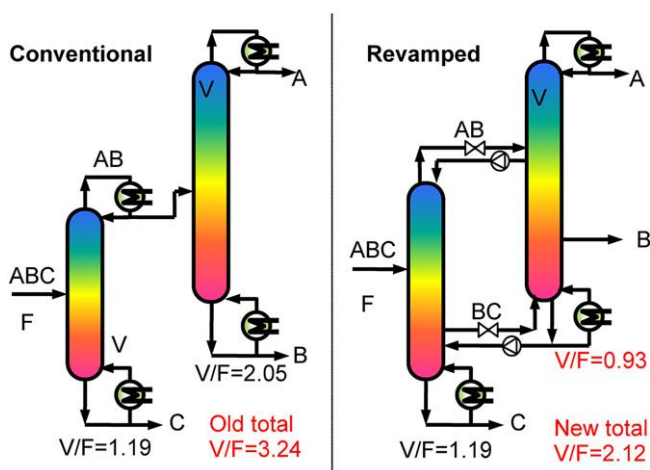


Fig. 12. Revamp to a fully thermally coupled arrangement may save up to 50% energy in the second column, and about 30% overall. The arrangement is thermodynamically equivalent to the Petlyuk arrangement in Fig. 5. The minimum stage numbers for 0.1% impurity are indicated.

is robust and simple, but usually one or both products have to be over-purified in order to have some margins to handle process disturbances like changes in feed properties. However, to operate at minimum energy for some specified product purities, both products must be controlled at their specifications, and not over-purified.

For Petlyuk arrangements like the DWC, the picture is a little more complicated because there are three “sub-columns” where drift may occur and there are interactions between the three sub-columns in the arrangement. However, we may use the same basic principles as for the conventional column. One needs one “stabilising” loop for each sub-column in the Petlyuk (DWC) to avoid drift.

A dividing wall (Petlyuk) column has 9 dynamic degrees of freedom (F, D, B, S, L, RI, Rv, Qb (V), Qc) for stabilizing control and, at the next level in the hierarchy, for composition control and optimisation. In a DWC it is common to have the vapour split (Rv) to each side of the dividing given by the design. With a fixed pressure (controlled using Qc) and feed rate, we are then left with 6 manipulated variables. Typically, the product streams in top and bottom (D,B) are used for level control in the top and the bottom of the column, and to stabilize the temperature profile in the three “sub-columns” we may select: Reflux L, Liquid split RI, and side-stream flow rate S and set a sufficiently large constant boilup V. It has been shown that it is necessary to operate the prefractionator close to the preferred split (Halvorsen and Skogestad, 1999b). With a given vapour split, the liquid split must be used for this purpose. To control all three product purities we also need to manipulate the boilup. It is also important to set the vapour split inside the optimality region, since the potential savings are easily lost if the DWC is not operated within the optimality region. Suboptimal operation is characterised by higher energy consumption, or inability to obtain high-purity, particularly in the side-stream (Halvorsen et al., 2009).

In practise it is common to control temperatures at selected stages since on-line composition measurement are expensive and less robust. Though, even if composition measurements are available, these are normally used in a cascade to adjust temperature setpoints in the control loops at the lower level. In a DWC, we must keep in mind that the control task is to maintain specified compositions and at the same time maintain optimal operation. The method of self-optimising control can be applied to find

a combination of measurements that, when used as a feedback variable, can be used to maintain optimal operation in presence of unknown disturbances and model uncertainties (Alstad, 2004).

A common academic approach is to find the optimal operating point by minimising energy for a given set of specifications. However, in practise the column will be operated close to its maximum production capability often given by the boilup capacity or flooding limit. Thus, if we specify the boilup vapour rate the optimisation target can then be to minimise the sum of impurities in the product streams. Based on this approach, Strandberg (Strandberg et al., 2010) has shown a feasible approach with four temperature control loops for a four-product Kaibel column.

### 6. Other energy saving arrangements

We will not go through all kind of possible arrangements, but in the lines of approaching the ideal reversible arrangement we look closer at some heat integration arrangements.

#### 6.1. Multi-effect columns and process integration

Multi-effect operation lets different section operate at different pressures to allow for internal heat exchange between sections. This kind of approach is well suited for revamp of existing plants, where we want to reduce the heat consumption without major replacement of columns.

Note that another important issue in both in revamp projects and in design of new plants is to adapt the heat levels in the distillation units to available utility heat levels. It may be a big difference if all the utility has to be produced by ordinary heater systems, or if heat is available from exothermic reactions like in a methanol plant.

Feed preheating will normally be less efficient than supplying all the heat in the reboiler. But, this may be beneficial in some cases. For example when preheating can be done with a lower temperature heat utility, this may save some higher temperature utility used for the reboiler.

In Double Effect Columns as shown by the examples in Fig. 13 pressure is adjusted at two levels ( $p_H$ : high,  $p_L$ : low) to obtain internal heat exchange within the arrangement between reboilers and condensers. However, this approach also affects the temperature span and thereby the actual minimum heat requirement

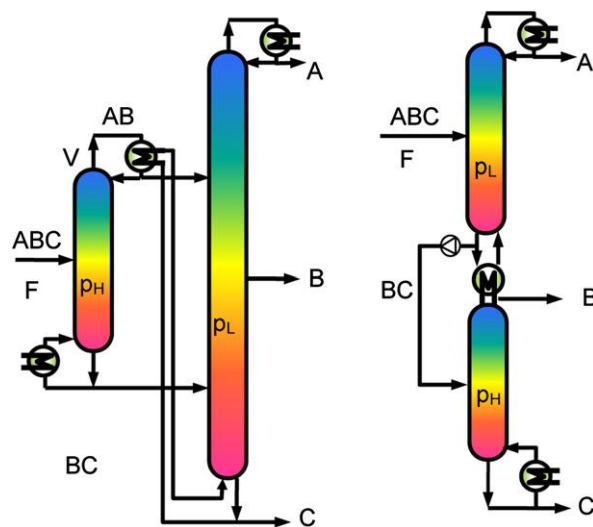


Fig. 13. Double Effect columns with heat integrated reboilers and condensers.

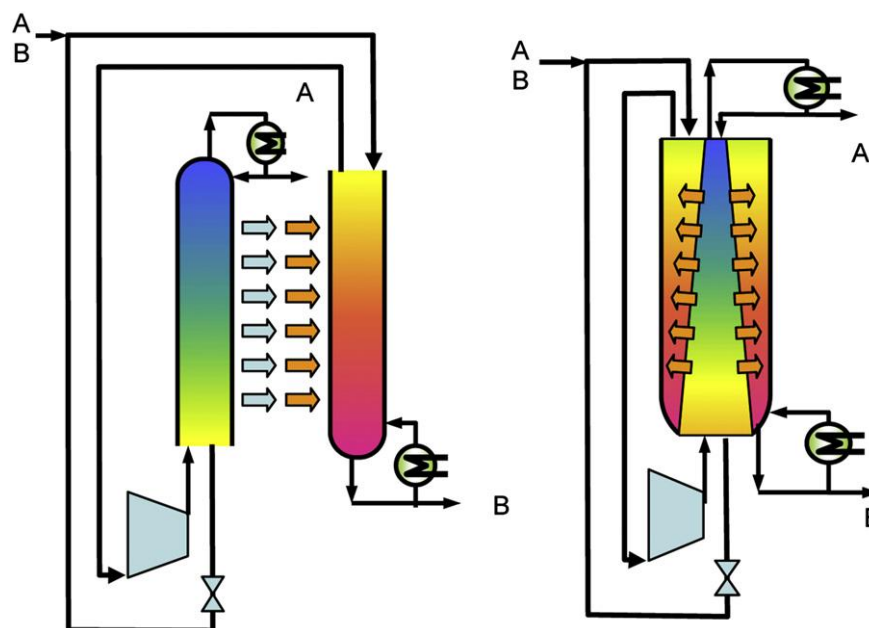


Fig. 14. HIDiC system.

according. Care must therefore be taken when comparing efficiency between different arrangements. The arrangements are based on the prefractionator arrangement in Fig. 4 and the direct split arrangement in Fig. 3.

### 6.2. Internally heat integrated columns HIDiC

A special configuration is the HIDiC where a compressor takes the vapour from the stripping section and increases the pressure into the rectifying section (Nakaiwa et al., 2003; Gadalla et al., 2007). In this way, heat can be transferred internally from the rectifying section to the stripping section as illustrated in Fig. 14. Due to the heating and cooling, the vapour flow rate will be highest around the feed stage, and is reduced towards the ends. This is indicated by a gradual change of the cross-section area.

The HIDiC clearly reduce the irreversible mixing loss within the sections and thereby also the need for external heat supply. However, we need to add compression work and this represent and extra high quality energy input and operating cost.

The HIDiC approach has high attention in Japan as illustrated by the following citation from paper 343d at the 2006 AIChE annual meeting (Ohe, 2006): *The HIDiC is evaluated highly as a chemical process in the international effort to combat global warming. In Japanese industry as a whole, 15% of all energy is expended in the chemical industry. In the chemical industry, separation by distillation expends 40% of total energy. For the basic study, a project was performed (1993–2000). The results are as follows. The energy saved was calculated as more than 30% over that of the same kind of plant operating with a conventional system. From April 2002 to March 2006 and the budget was 1,400,000,000 yen (about US \$12,730,000 at that time).*

## 7. Conclusion

Reduced total energy consumption must be a high priority objective for industrial applications. In practise this implies that fully thermally coupled arrangements and other energy efficient arrangements must always be considered whenever any separation system shall be designed, both for new applications and plant modifications. Thus, the obtained knowledge of design and

operation must be made available to chemical engineers, so we avoid building new old-fashioned distillation systems when more energy efficient solutions actually would be feasible and beneficial to the plant. There is a challenge to researchers in spreading the knowledge, and to plant owners and engineering companies to pick up and implement the new energy saving technology. However, we do not claim that use of DWC or equivalents always will fit in. In many cases, the well proven direct or indirect split will be competitive and a good choice, but energy saving structures should always be seriously considered. We anticipate that the portion of fully thermally coupled arrangements can be increased from now on and thereby contribute to a significant reduction of the total energy consumption used for distillation worldwide.

The presented structures and computation methods are tools to realise energy saving distillation arrangements.

## References

- Agrawal, R., 1999. More operable fully thermally coupled distribution column configurations for multicomponent distillation. *Chemical Engineering Research and Design* 77, 543–553.
- Agrawal, R., 2001. Separations: perspective of a process developer/designer. *Aiche Journal* 47, 967–971.
- Alstad, V., 2004. Combination of Measurements as Controlled Variables; Application to a Petlyuk Distillation Column, IFAC Symposium on Advanced Control of Chemical Processes (ADCHEM) Hong Kong.
- Christiansen, A.C., Skogestad, S., Lien, K., 1997. Complex distillation arrangements: extending the Petlyuk ideas. *Computers & Chemical Engineering* 21, S237–S242.
- Dejanović, I., Matijašević, L., Olujić, Ž., 2010. Dividing wall column—A breakthrough towards sustainable distilling. *Chemical Engineering and Processing* 49, 559–580.
- Dejanović, I., Matijašević, L., Halvorsen, I.J., Skogestad, S., Jansen, H., Kaibel, B., Olujić, Ž., 2011. Designing four-product dividing wall columns for separation of a multicomponent aromatics mixture. *Chemical Engineering Research and Design* 89, 1155–1167.
- Petlyuk, F.B., Platonov, V.M., Slavinskii, D.M., 1965. Thermodynamically optimal method for separating multicomponent mixtures. *International Chemical Engineering* 5, 555–561.
- Fonyo, Z., 1974. Thermodynamics analysis of rectification I. Reversible model of rectification. *International Chemical Engineering* 14, 18–27.
- Gadalla, M., Jimenez, L., Olujić, Z., Jansens, P.J., 2007. A thermo-hydraulic approach to conceptual design of an internally heat-integrated distillation column (i-HIDiC). *Computers & Chemical Engineering* 31, 1346–1354.

- Grunberg, J.F., The reversible separation of multicomponent mixtures, in: Proceedings of the 1956 Cryogenic Engineering Conference, Boulder Colorado, 1956.
- Halvorsen, I.J. Minimum energy requirements in complex distillation arrangements, NTNU PhD Thesis 2001:43, 352.
- Halvorsen, I.J., Skogestad, S., Optimal operation of Petlyuk distillation: steady-state behavior, Journal of Process Control Proceedings of the 1997 6th International Symposium on Process Systems Engineering and 30th European Symposium on Computer Aided Process Engineering (PSE-ESCAPE'97), May 25–May 29 1997, 9 (1999a), pp. 407–424.
- Halvorsen, I.J., Skogestad, S., 1999b. Optimal operation of Petlyuk distillation: steady-state behavior. Journal of Process Control 9, 407–424.
- Halvorsen, I.J., Skogestad, S., 2003a. Minimum energy consumption in multicomponent distillation. 3. More than three products and generalized Petlyuk arrangements. Industrial & Engineering Chemistry Research 42, 616–629.
- Halvorsen, I.J., Skogestad, S., 2003b. Minimum energy consumption in multicomponent distillation. 1. V-min diagram for a two-product column. Industrial & Engineering Chemistry Research 42, 596–604.
- Halvorsen, I.J., Skogestad, S., 2003c. Minimum energy consumption in multicomponent distillation. 2. Three-product Petlyuk arrangements. Industrial & Engineering Chemistry Research 42, 605–615.
- Halvorsen, I.J., Skogestad, S., 2006. Minimum Energy for the four-product Kaibel-column. In: AIChE Annual Meeting, AIChE, San Francisco Paper 216d.
- Halvorsen, I.J., Skogestad, S., 2009. Minimum energy operation of Petlyuk distillation columns-Nonsharp product specifications. In: Proceedings of the 1st Annual Gas Processing Symposium. Elsevier, Amsterdam, pp. 79–87.
- Kaibel, G., 1987. Distillation columns with vertical partitions. Chemical Engineering and Technology 10, 92–98.
- Kaibel, G., Miller, C., Stroezel, M., von Watzdorf, R., Jansen, H., 2004. Industrial application of dividing wall distillation columns and thermally coupled distillation columns. Chemie Ingenieur Technik 76, 258. +.
- Kolbe, B., Wenzel, S., 2004. Novel distillation concepts using one-shell columns. Chemical Engineering and Processing 43, 339–346.
- Nakaiwa, M., Huang, K., Endo, A., Ohmori, T., Akiya, T., Takamatsu, T., 2003. Internally heat-integrated distillation columns: a review. Chemical Engineering Research and Design 81, 162–177.
- Ohe, S., An overview of a Japanese National project: development of technology for energy-saving distillation through internal heat exchange (Hidic), in: AIChE Annual Meeting, San Francisco, 2006.
- Olujic, Z., Jödecke, M., Shilkin, A., Schuch, G., Kaibel, B., 2009. Equipment improvement trends in distillation, Chemical Engineering and Processing. Process Intensification 48, 1089–1104.
- Parkinson, G., 2007. Dividing-wall columns finds greater appeal. Chemical Engineering Progress 103.
- Petlyuk, F.B., Platonov, V.M., Girsanov, I.V., 1964. The design of optimal rectification cascades. Khim Prom 45, 445–453.
- Shah, V.H., Agrawal, R., 2009. A matrix method for multicomponent distillation sequences. Aiche Journal 9999 (NA).
- Skogestad, S., 2007. The dos and don'ts of distillation column control. Chemical Engineering Research and Design 85, 13–23.
- Smith, R., 2005. Chemical Process Design and Integration. J. Wiley & Sons.
- Stichlmair, J., 1988. Distillation and rectification. In: Ullmann's Encyclopedia of Industrial Chemistry. Wiley-VCH.
- Strandberg, J., Skogestad, S., Halvorsen, I.J., Practical control of dividing wall columns, in: Proceedings of distillation and Absorption 2010, Eindhoven, The Netherlands, 2010, pp. 527–532.
- Triantafyllou, C., Smith, R., 1992. The design and Optimization of fully thermally coupled distillation-columns. Chemical Engineering Research and Design 70, 118–132.
- Wolff, E.A., Skogestad, S., 1995. Operation of integrated 3-Product (Petlyuk) distillation-Columns. Industrial & Engineering Chemistry Research 34, 2094–2103.