Energy Management

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Introduction

Distillation dominates separation processes in the petrochemical industry and consumes nearly 95% of the total energy used in commercial separations. The energy used in distillation is approximately 3% of the total energy consumed in US industry. Distillation columns provide reliable, cost-effective separation for large throughputs and high purity product requirements. Distillation is an energy-intensive process and economics drive the need to optimize energy consumption in all aspects of its design.

In the pioneer years of distillation development, energy was comparatively cheap compared to capital costs. Reflux ratios of 1.2–1.5 times the minimum were commonly used to obtain an economical balance between operating and fixed costs. Columns were designed with large design margins to allow for feed changes and the lack of accuracy in physical properties, tray hydraulics and tray efficiency. By providing excess exchanger and tray capacity, product purity could be maintained by adjusting the tower operation to compensate for design uncertainty.

With the advent of the oil crises of the 1970s and 1980s, the energy costs became the major factor in column costs and created an urgency to find ways to reduce the energy requirements of distillation. Several techniques for analysing columns and plants were extensively developed and published in this era. Among the notable advances is ‘exergy’ analysis, developed primarily in Europe, and ‘pinch’ technology. This trend has subsided somewhat as more efficient methods of design and experience have eventually replaced the older technologies. The more exciting opportunities are in revamping older plants and designing new products. The introduction of high speed computers has also played a significant role in producing more accurate and more extensively evaluated designs. Physical and transport properties continue to be obtained more accurately. As the regulatory requirements for pollutant emissions and wastewater reduction became more stringent, many new studies has been directed towards reducing emissions from fired heaters and steam boilers used to supply heating requirements in columns. Wastewater reductions of steam condensate blowdowns and cooling water make-up have become subject to tighter restrictions. Distillation column design will become more extensive and complex as the stringency of requirements continues to increase.

The primary objective of distillation column design is to produce the desired products with the minimum amount of energy expenditure and capital cost. The energy consumption in distillation columns is affected by the physical properties of the system, the utilities available for heating and cooling, the internals for contacting the liquid and vapour and the arrangement of the column separation sequence.

Measurement of Energy Performance

In order to determine the energy performance of a distillation column, two thermodynamic principles are applied to give a measurement method for determining the value of design improvements.

Availability or Exergy Analysis

The concept of availability or available useful work is a convenient way to determine the thermodynamic minimum amount of energy required for doing work in a steady flow process. The availability is referred to as exergy in Europe. The availability function is defined as:

$$A \equiv H - T_a S$$

where H is the enthalpy, S is the entropy and T_a is the reference temperature (298 K). A higher value of availability indicates that more work can be extracted as compared to a lower value. For example, high pressure steam is more valuable than steam at atmospheric pressure, although the latent heat values are about equal.

The change in availability represents the amount of shaft work that can be extracted from a system as it flows from an initial to final state. It also defines the minimum work required to achieve a change in a flowing system. This available shaft work, W_s, is defined in terms of the availability change, or:

$$-W_s \equiv \Delta A = \Delta H - T_a \Delta S$$

These properties are readily available from data references or process simulators and can be applied to all types of plant equipment in a process.

Heat Engines

A Carnot heat engine is useful in determining the theoretical maximum heat efficiency of an ideal, reversible distillation. The heat engine analogy consists of the simple column arrangement depicted in **Figure 1**. Heat is added at the bottom of the tower at a high level of temperature and then removed at the top of the tower at a lower temperature. This degradation in heat provides the work to separate the feed into the products. If we consider a distillation column as a heat engine, then the theoretical minimum work required for the heat engine is:

$$W_{\mathrm{heat}} = Q_{\mathrm{reboiler}}(1 - (T_{\mathrm{a}}/T_{\mathrm{reboiler}})) - Q_{\mathrm{condenser}}(1 - (T_{\mathrm{a}}/T_{\mathrm{condenser}}))$$

The availability change of the streams in and out of the column is equal to this heat work minus a lost work term to account for thermodynamic inefficiency, or:

$$A_{\mathrm{products}} - A_{\mathrm{feeds}} = W_{\mathrm{heat}} - W_{\mathrm{lost}}$$

To account for real processes, a lost work term is included to account for irreversible changes within the column. This extra work is required to overcome pressure, temperature and composition driving forces. There are a number of commercial algorithms for determining each driving force contribution to lost work. These lost work contributions are generally classified as:

1. Momentum loss due to pressure drop.
2. Heat transfer loss from temperature difference.
3. Mixing losses due to composition differences.

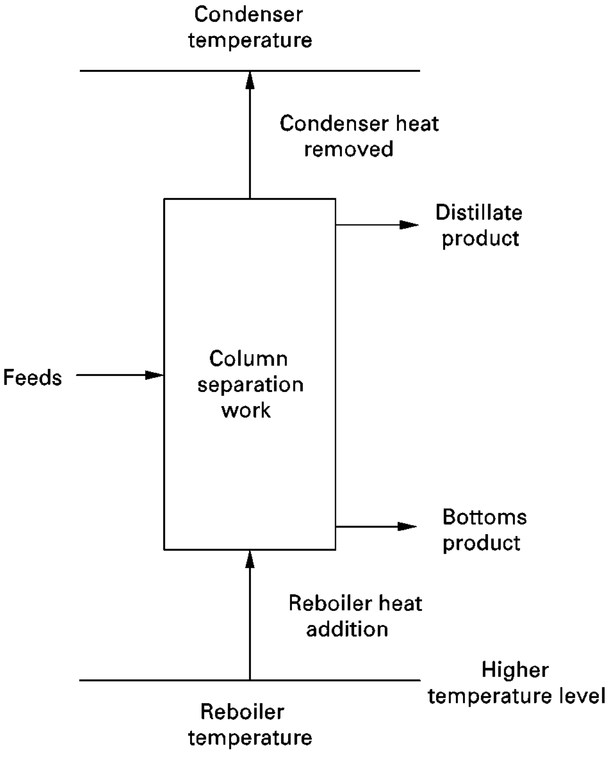

Figure 1 Distillation heat engine analogy.

As the lost work term increases, the reboiler and condenser loads must increase in order to supply the same amount of useful work. As the driving forces approach zero, the lost work approaches zero and less energy is wasted.

For a particular column design, the availability of the feed and products and the theoretical minimum work are fixed. The lost work energy is solved by difference. The actual heat duty required for the distillation column will be the sum of the theoretical minimum plus the lost work, or ($W_{\mathrm{heat}} + W_{\mathrm{lost}}$). By comparing values of this sum, the designer has a yardstick in which to rate different column designs. For existing columns, a simple calculation of the total lost work will quickly focus as approach towards the most potentially beneficial areas. For example, if the lost work is less than 5% of the total heat duty, then this is probably within the design margin of the equipment and not worth pursuing.

Distillation Design Guidelines

A thermodynamic analysis provides information about the theoretical limits and does not address the issues of expense and implementation. Exergy studies should include capital costs with a payback period for a proper economic assessment.

The following list is a collection of design guidelines and practical constraints to be considered in searching for better energy schemes:

1. In order to distil vapour and liquids, the pressure must be below the critical pressure.
2. Accurate physical properties are required; proper models for nonideal solutions and azeotropes should be checked.
3. Thermally unstable components may limit the reboiler temperatures.
4. Air and/or water-cooling are preferred to the more expensive refrigeration.
5. Operational flexibility is usually required for feed changes and plant turndown.
6. Distillation columns do not work well at less than the minimum reflux ratio and at pinch points.
7. Heat integration may not be practical; transporting fluid over large distances may not be econ-

omical; excessive temperatures result in film boiling; interaction between columns should be controlled.

8. Shipping weight and total height restrictions tend to limit the maximum number of trays or packing in one tower shell.
9. Lowering the operation pressure is a simple way to reduce energy consumption. Increasing pressure is the simpler way to increase capacity.
10. Lower energy consumption usually requires higher capital costs.

McCabe–Thiele Diagrams

One of the best visual aids for distillation is the ubiquitous McCabe–Thiele diagram. Despite its many limitations, the diagrams show the basic relationship between the equilibrium curve and the composition profiles throughout the column. A typical McCabe–Thiele diagram is illustrated in **Figure 2**. Heating or cooling changes the internal vapour and liquid flows and this effect can be seen as a shift in the slope of the operating lines in the diagram. For energy management, we are interested in seeking ways to minimize the difference (the composition driving forces) between the operating and equilibrium curves.

The absolute minimum energy expenditure will occur if external heating or cooling is applied to each stage to adjust the operating line so that it coincides with the equilibrium curve. This condition is impractical, since an infinite number of stages would be required. The goal is to design a column with an approach as close as possible to equilibrium, but with an acceptable number of stages. A few successful designs exist that provide internal continuous cryogenic cooling in a small tray section. These types of columns that have continuous, internal heat exchangers are called dephlegmators.

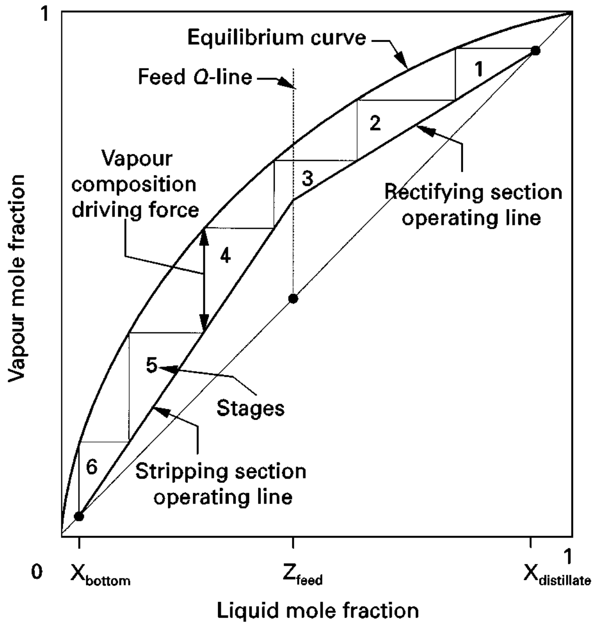

Figure 2 Typical McCabe–Thiele diagram.

There are numerous practical applications in the industry where adding *just a few select* external heating or cooling locations will provide a cost-effective reduction in energy.

Intermediate Heating and Cooling

Pumparounds

One of the earliest methods for saving significant amounts of energy was developed for crude units. Pumparounds are used extensively in atmospheric and vacuum towers to remove heat at selected stages. Liquid is withdrawn from an intermediate product stage, externally cooled and then pumped back to the column at a higher elevation. This arrangement is shown in **Figure 3**. The hot liquid from the tower is used to supply heat to several sources. The remaining cooled liquid is returned to the column and used to cool the column vapour. Pumparounds have the effect of shifting the operating lines *at select intervals* closer to the equilibrium curve to improve energy consumption. The sub-cooled liquid provided in the pumparound reduces the cold utility requirements and size of the overhead system. The cooling tower and condensers are less expensive and thermal and wastewater pollution is reduced. The hot pumparound liquid has the additional role of recovering heat supplied in the feed furnaces by transferring it to feed pre-heat, steam generation and heating for downstream units.

Intercondensers and Interreboilers

Another useful technique for reducing the utility loads is to add intermediate exchangers. **Figure 4** shows the effect of adding an inter-reboiler on a McCabe–Thiele diagram. The benefit of this modification is that the *reboiler* heat duty is reduced by the amount of duty used in the inter-reboiler. Since the temperature level will be less than the reboiler temperature, it may be possible to use a process stream for the heating. If this heat integration is feasible, then significant savings of the reboiler utility, such as high pressure steam, can be achieved. The internal column flows below the interreboiler stage will be reduced, but the stage requirement will increase since the operating line will be closer to the equilibrium curve. For this reason, the addition of intermediate exchangers is

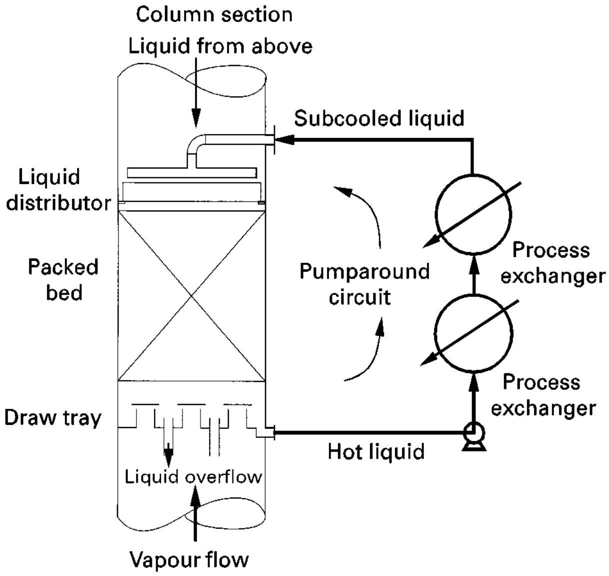

Figure 3 Pumparound section.

usually economical only when a few extra stages will be required. An analogous result will be obtained with an inter-condenser. The condenser utility load will be reduced, the internal flows in the stages above the condenser will be reduced, but more stages will be required. The benefits of intermediate cooling or condensing are particularly economical when an expensive refrigerant is used as the condenser cooling medium.

There are semi-rigorous calculation methods for determining how much heat can be added or removed at a particular temperature level. One technique, which is an extension of 'pinch' technology, is to generate a column grand composite curve (CGCC). These curves plot the heat transferred between the vapour and liquid versus stage temperature. A typical example is shown in **Figure 5**. The best opportunities for using intermediate heat exchangers exist in the regions where large amounts of heat are exchanged at temperatures significantly different to that of the reboiler or condenser. When deciding upon how much heat will be added or removed, one should consider the extra stages that will be required and allow for a suitable design margin for flexibility. If this type of region exits near the feed locations, then feed conditioning may be an option. Adding a feed exchanger will generally be less expensive than adding an intermediate exchanger on the column.

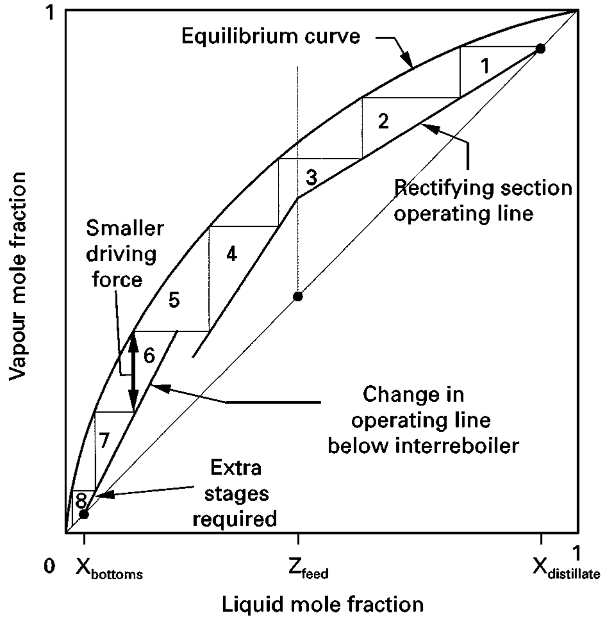

Figure 4 McCabe–Thiele diagram with interreboiler.

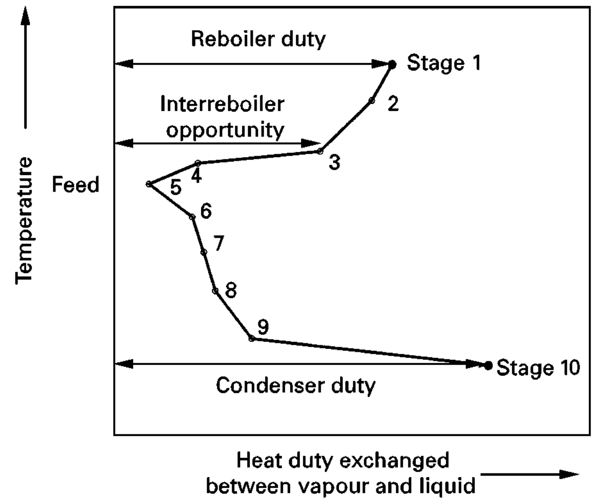

Figure 5 Column grand composite curve.

Feed Conditioning

The feed is introduced into the column where the temperature and composition roughly match the column profile. The feed is at higher pressure in order to flow into the column. The location of the feed stream can be optimized with a few judicious choices with a process simulator. The feed quality and location can also be adjusted within limits to lower the reboiler or the condenser duty, but not both. The best opportunities for utilizing feed exchangers are during revamps when there is excess vapour- and liquid-handling capacity in one section of a column. For example, if the trays above the feed can handle more fluid traffic without modification, but the bottom section trays are capacity-limited, then installing a feed preheater can be used to unload the bottom traffic. The energy penalty will be increased condenser duty, but internal modifications or tower replacement may be avoided.

Prefractionation

In a multi-component column separation, the presence of lighter nonkey components will limit the purity of the light key. At the top of the tower, the light key will actually be the heavier component and its composition will reach a maximum value and then decrease as it is fractionated from the lightest components. By removing these lighter non-key components from the feed in a pre-absorber, the column can now produce a higher purity product. Removing the light components from the feed reduces the flow to the column, so that pre-absorbers can be used to unload the rectifying section of an existing column. In analogous fashion, the addition of a pre-stripper will unload heavy components from the stripping section of a column. **Figure 6** shows an illustration of a pre-stripper column arrangement. The additional feed to the last column will usually provide a modest energy saving for that column.

Heat Pumping

A significant saving in condenser duty can be achieved by compressing the overhead vapour to a temperature that can be used to reboil the bottoms liquid. A typical heat-pumped column is shown in **Figure 7**. The compressor is a significant addition to the total capital costs. This scheme is feasible if the distillation involves a close boiling mixture where the top and bottom temperatures are not significantly different. The most common industrial application is propane/propylene splitters, which require large amounts of heating and cooling energy. A large reduction in cooling water and wastewater products provides a large incentive to heat pump these types of columns.

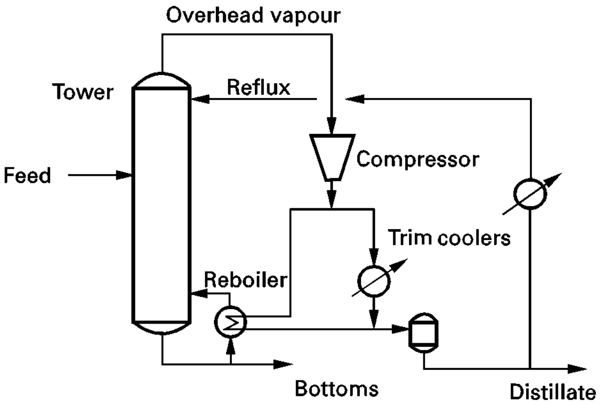

Figure 7 Heat-pumped column.

Extractive and Azeotropic Distillation

Instead of modifying the heat exchange in columns, a reduction in energy is possible by altering the physical properties of the mixtures. For mixtures that are difficult to distil, a solvent may be added to increase the relative volatility of the mixture. If a suitable solvent can be found with a relatively low volatility, then the separation process is known as extractive distillation. A typical extraction distillation column arrangement is illustrated in **Figure 8**. This process is economical to use when a small amount of inert solvent can permit an easier (less expensive) separation of the original products. An additional tower is required to remove the solvent from the heavier product.

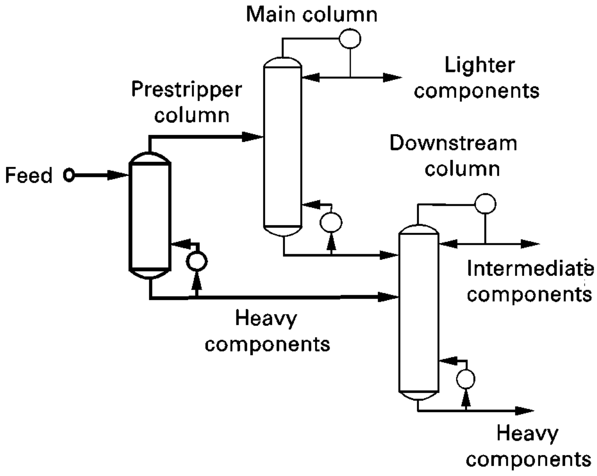

Figure 6 Prestripper column sequence.

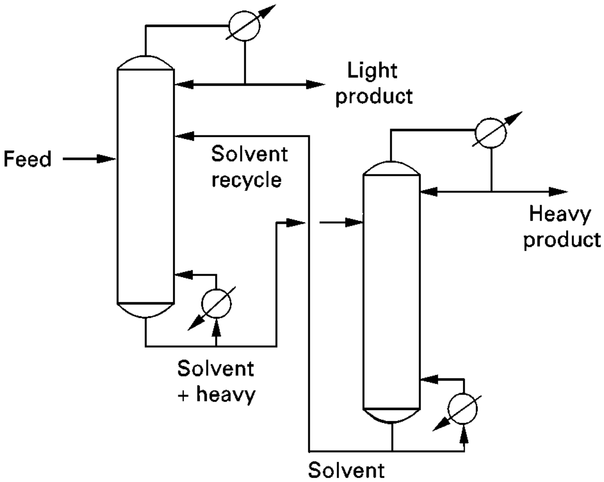

Figure 8 Extractive distillation configuration.

If the addition of a light component can alter an azeotrope, then the process is termed azeotropic distillation. The entrainer often forms a new low boiling azeotrope that is relatively easy to separate from the heavier product. The entrainer is separated from the lighter product with an additional column and/or condensed to two liquid phases that are separated in a settling drum. Azeotropes are common in the specialty chemicals industry and most configurations are proprietary.

Extractive or azeotropic distillation should be considered a last resort option. Finding a suitable solvent or entrainer that is inexpensive and relatively inert is the key to a practical design.

Column Internals Selection

The choice of internals can have impact on energy efficiency, control response and downstream equipment. The function of trays or packing is to promote efficient heat and mass transfer by intimate contacting of the vapour and liquid. For trays, a portion of the vapour energy is expended in the form of pressure drop to produce liquid droplets and to overcome the liquid head on the tray. In contrast, the contact area in packing is mainly created by the spreading of liquid over the metal surfaces and by rivulet flow. For these reasons, the pressure drop in packing is significantly less than in trays.

This becomes an important characteristic in high vacuum distillation, where the pressure and temperature changes dramatically from top to bottom as pressure drop increases. A tower pressure change from 50 mm Hg to 25 mm Hg will double the volumetric flow of vapour and will have a major impact on the tower size. The normal design pressure drop for *one* tray is 3–5 mm Hg, which will limit the number of trays that can be used. Low pressures and temperatures in the top of the tower have an impact on the cost and performance of the condenser and vacuum system. Using lower pressure drop internals reduces the exergy losses associated with momentum and temperature difference. For these reasons, packed ns are favoured for vacuum distillations.

There also is an advantage to lowering pressure drop in a column when the overhead vapour is fed to a compressor. Changing from trays to packing during a capacity increase revamp is a convenient way to avoid compressor changes. If the pressure drop through the tower is reduced, the increase in compressor suction pressure may just compensate for the new capacity increase.

By virtue of lower pressure drop and liquid holdup, packed columns have relatively faster response to changes in flow and composition changes. The faster acting control of the column reduces the energy waste of recycling off-spec product.

Column Sequencing

The sequencing and arrangement of columns to obtain multiple products has a major impact on energy and capital costs. In order to separate X amount of products, a minimum of $X - 1$ simple, conventional columns are required. If the products are removed as distillates, the arrangement is called a direct sequence. The direct sequence is favoured when the distillations are at high pressure and require refrigeration, such as olefin production. An indirect sequence is used if the products are withdrawn as bottoms. Indirect sequencing favours lower heat consumption. In many petrochemical plant configurations, both sequences are used or mixed as dictated by the many product requirements. An illustration of the direct and indirect sequence arrangement is given in **Figures 9** and **10**.

A number of heuristics have evolved from experience of sequencing columns. A few of the more common guidelines are listed below:

1. Leave the most difficult separations to the end. The binary separation of high purity products requires larger towers and higher energy consumption when non-key components are present.
2. Direct sequences are favoured when heating costs are less than cooling costs.
3. Less energy is expended when the top and bottom product flows are about equal.

The column sequencing depends upon numerous factors that make each case different. Refining, ethylene, aromatic and specialty chemical plants all have unique properties and idiosyncrasies that make generalizations difficult. The column arrangements

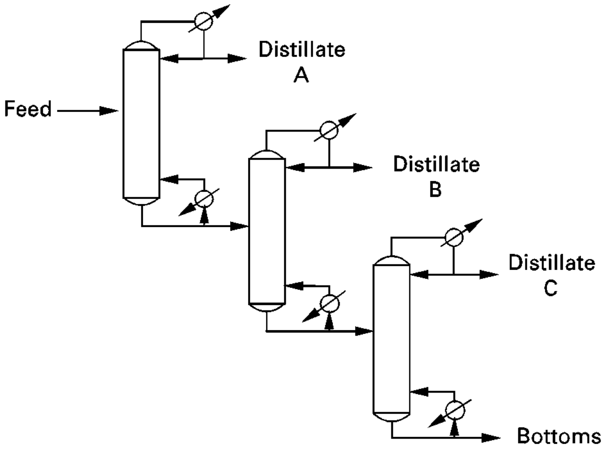

Figure 9 Direct column sequence.

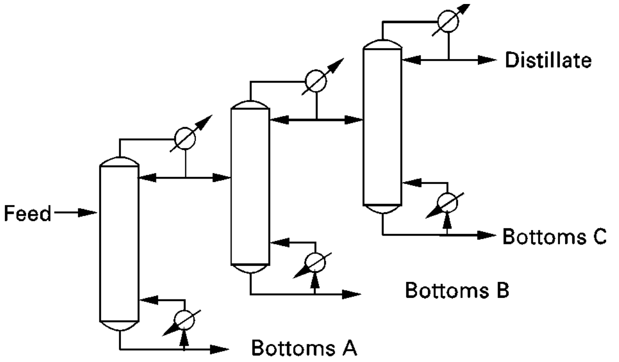

Figure 10 Indirect column sequence.

are commonly integrated with the total plant optimization to minimize overall capital costs, energy consumption and pollution reduction. Techniques such as pinch technology and exergy analysis are used to evaluate the global effect of equipment changes to arrive at the best plant design, which may not coincide with the best column design.

Distributed Distillation

Distributed distillation is a separation technique that minimizes the lost work due to mixing and recycling of fluids within a column. The energy consumption can be reduced by making a separation between the most volatile and least volatile components with the rest of the components distributed between the top and bottom. An easy separation between components with the highest relative volatility will yield the minimum boil-up and reflux for any column. This concept is illustrated in **Figure 11**. A distributed column sequence will theoretically consume less energy, but will require more columns. The energy savings have been reported to be upwards of 30%.

To lower the capital costs, the column can be thermally coupled as described in the Petlyuk configuration shown in **Figure 12**. Thermal coupling is used to describe the situation when liquid from a column is used to supply reflux and vapour is used to supply boil-up to another column. Several variations of this arrangement are used to eliminate heat exchangers in column designs. Combining the two columns together and providing a partition to form a *divided wall column* reduces the capital cost. Three products can be produced from one column, one reboiler and one condenser, as compared to a conventional sequence that requires two columns and four exchangers. The commercial use of divided wall columns tends to be limited to separations with significant amounts of intermediate components.

The Future of Energy and Distillation

Distillation is a mature separation technology and will remain dominant in the near future. Despite the high energy requirements, distillation is a cost-effective method for separating large quantities of material into high purity products. Other separation methods are specific in application and lack the

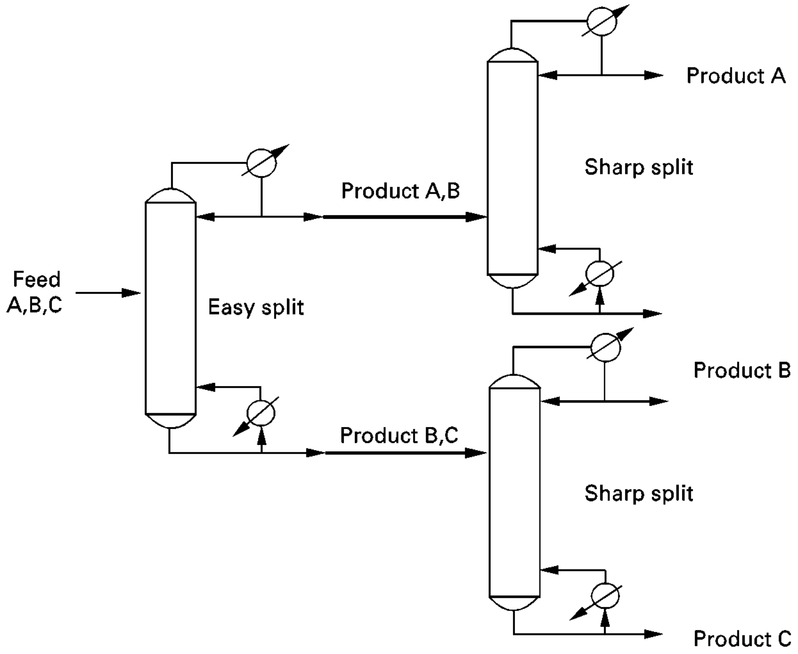

Figure 11 Distributed column sequence.

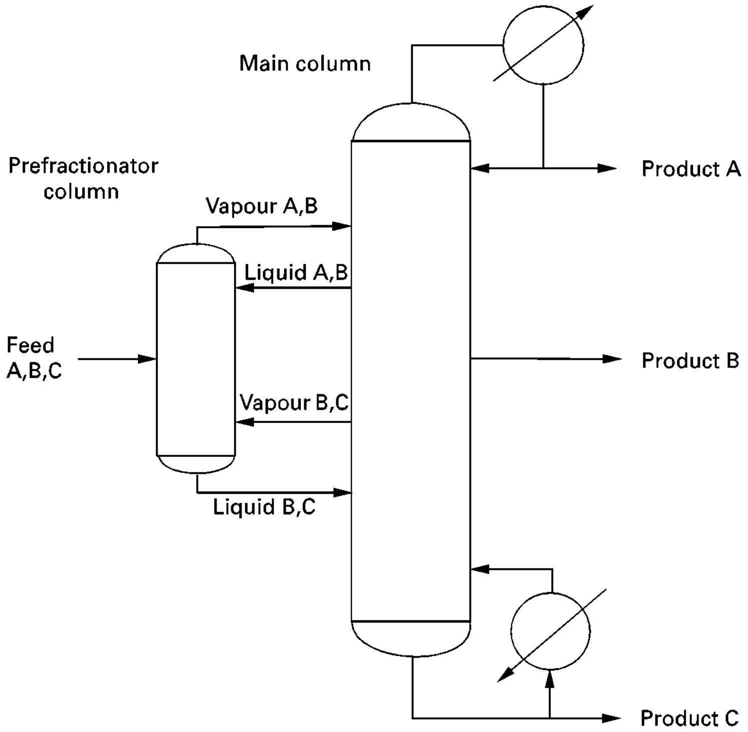

Figure 12 Petlyuk configuration.

versatility of distillation. Current research efforts have been evolutionary and the majority of the industry is reluctant to test any technology that has not been commercially proven. Therefore, even promising new technology changes are slow and cautious. Many research efforts have started to combine the best features of different separation methods to save energy and capital costs. The future of distillation will always depend upon energy costs and change will occur when these costs become unacceptable.

See also: **II/Distillation:** High and Low Pressure Distillation; Historical Development; Modelling and Simulation; Multicomponent Distillation; Packed Columns: Design and Performance; Pilot Plant Batch Distillation; Theory of Distillation; Tray Columns: Design; Vapour-Liquid Equilibrium: Theory.

Further Reading

Dhole VR and Linhoff B (1993) Distillation column targets. *Computers in Chemical Engineering* 17 (56): 549–560.

Dodge BF (1994) *Chemical Engineering Thermodynamics*. New York: McGraw-Hill.

Fonyo Z (1974) Thermodynamic analysis of rectification–I. Reversible model of rectification. *International Chemical Engineer* 14(1): 18–27.

Kaibel G Blass E and Kohler J (1990) Thermodynamics–guidelines for the development of distillation column arrangements. *Gas Separation and Purification* 4: 109–114.

Kaibel G (1992) Energy integration in thermal processengineering. *International Chemical Engineer* 32 (4): 631–641.

King CJ (1971) *Separation Processes*. New York: McGraw-Hill.

Liebert T (1993) Distillation feed preheat – is it energy efficient? *Hydrocarbon Processing* 3: 37–42.

Linhoff B, Dunford H and Smith R (1983) Heat integration of distillation columns into overall process. *Chemical Engineering Science* 38: 1175–1188.

Petterson WC and Wells TA (1977) Energy-saving schemes in distillation. *Chemical Engineer* (September): 78–86.

Sussman MV (1980) *Availability* (*Exergy*) *Analysis*. Lexington, MA: Mulliken House.

Terranova BE and Westerberg AW (1989) Temperature–heat diagrams for complex columns. I. Intercooled/interheated distillation columns. *Ind. Eng. Chem. Res.* 28: 1374–1379.

Treybal RE (1968) *Mass-Transfer Operations*, 2nd edn. New York: McGraw-Hill.

US Department of Energy (1994) *Assessment of Potential Energy Savings in Fluid Separation Technologies*. Document DOE/ID/124763-1, December. Washington, DC: US Department of Energy.

Vogler TC (1988) Thermodynamic availability analysis for maximizing a systems efficiency. *C.E.P.* 25–42.