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How to Improve the Energy Savings in Distillation and Hybrid Distillation-Pervaporation Systems

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Abstract: As the worldwide demand for energy is growing, engineers are facing a challenge to design plants with minimum energy requirements. Distillation is an energy intensive process regardless of the products being separated. Using as an example the separation of alcohol–aqueous mixture, this article describes some options applicable to both revamp and new installations where the reduction of energy consumption is achieved. The "Hybrid" application is represented by the Water-Tetrahydrofurane (THF) separation comparing a conventional two column Pressure Swing Distillation(PSD) system with a pressure distillation using a membrane unit. The main focus is on energy savings for a given separation problem trough the introduction of membrane unit.

Keywords: Distillation, pervaporation, membrane technology, divided wall column

INTRODUCTION

Energy saving has become an important factor for chemical and petrochemical processing plants. The high energy costs, economic conditions, and market fluctuations are forcing each company to take action to keep operating cost at the lowest possible level.

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Distillation is an energy intensive process. It consumes about 40% of the total energy used in the chemical and petroleum refining industries. The energy used per unit weight of product is a simple and reliable measure for the quantification of the energy reduction. Almost every column in operation today can be retrofitted with attractive economic benefits. Considering distillation as a low efficiency process, every possible improvement that brings some return of investment is valuable (1).

In order to improve the performance of distillation, a different approach can be taken depending on the process requirements and available energy sources. It is possible to:

- Improve the existing process by using high-efficiency internals either for improved performance or capacity increase.
- Use enhanced distillation configurations with column thermal couplings and other means of heat integration.
- Use novel distillation technology providing energy and capital cost improvements, such as Divided Wall Column technology
- Use a hybrid system with pervaporation that will create an alternative process and which will provide economical and process benefits.

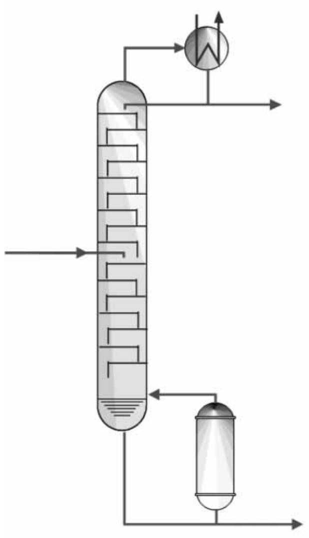
Improvement of an Existing Distillation System

An existing methanol/water separation has been analyzed for the potential of energy savings. The column has a diameter of 6 ft, and has 33 one-pass round valve trays, twenty–three trays above and ten trays below the feed. Process conditions and separation requirements are presented in Table 1. A tray efficiency of 70%—typically observed in this application—has been assumed, resulting in a total of 25 theoretical stages, including condenser and reboiler. Simulation results are presented in Fig. 1.

Hydraulic calculations show that the existing column is in a stable operating mode for the given operating conditions (Fig. 2). However, a capacity increase of only a few percent can bring the column to the jet flood operational limit, and further capacity increase will cause the column to flood. Operating hydraulic conditions are well described using

Table 1. Methanol/water separation requirements

Feed rate, lb/hr	22,046
Overhead operating pressure, psia	15.95
Feed temperature, °F:	176
Feed composition–methanol, wt%	80
Feed composition–water, wt%	20
Top specification–water, wt%	0.01
Bottom specification–methanol, wt%	0.01



TOP PRODUCT

Component	Wt%	Lb/hr
Methanol	99.99	17,636.5
Water	0.01	1.76
TOTAL:	100	17638.3

FEED

Component	Wt%	Lb/hr
Methanol	80	17,637
Water	20	4,409.2
TOTAL:	100	22,046

BOTTOM PRODUCT

Component	Wt%	Lb/hr
Methanol	0.01	0.44
Water	99.99	4,407.4
Total:	100	4,407.9

Condenser Duty , MMBTU/hr	-23.59
Reboiler Duty , MMBTU/hr	23.68
Top Temperature, ºF:	151.9
Bottom Temperature, ºF:	227.1

Figure 1. Methanol/water column simulation results.

the tray-performance diagram, as presented in Fig. 2. Performance diagrams are a simple way of presenting the full operating flexibility for trays as all pertinent hydraulic parameters and all operating points can be placed in a single graph. Stable operating conditions are represented by the operating

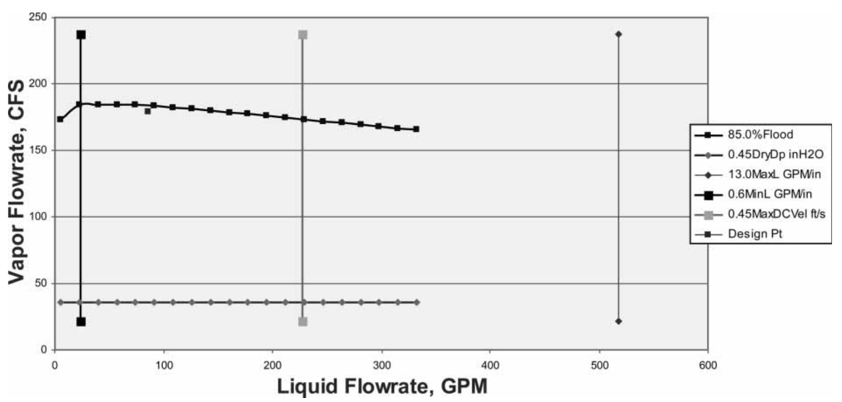


Figure 2. Tray performance diagram.

point being located in between the boundary lines; jet flood as a top boundary, minimum tray dry pressure drop as a bottom boundary and maximum and minimum liquid load located on a left and right sides of operating window. The operating point for the top column section lies within the operating window however it is closely located to the upper limit of the jet flood. This column has been pushed to its maximum hydraulic capacity.

In typical revamp situations the first choice is to evaluate the use of high efficiency internals, either trays or structured packing. In this case, taking into consideration a non-fouling system and low to moderate operating pressures, structured packing internals are a good choice. This is especially true with the advent of high-performance structured packing. The principle behind the latest generation of high-performance structured packing is to avoid premature flooding between the packing elements. The initial flood point of conventional structured packing is characterized by the buildup of liquid holdup in the lower portion of the packing element. Holdup measurement data from Sulzer Chemtech have revealed that flooding in conventional structured packing starts at the horizontal element interfaces where two elements of packing contact each other. Flooding then spreads upwards into the bulk of the element. The liquid buildup occurs due to hydraulic disturbances in this transitional section between the elements of the packed bed. The gas flow is forced to a sudden change of the flow direction resulting in increased shear forces at the gas/liquid interface and therefore additional local pressure drop. Additionally the increased film thickness at the bottom of each element leads to a reduction of the free open area for the gas flow. Increased gas velocity causes earlier flooding (2).

New high-performance structured packings have been developed to effectively minimize this disturbance by smoothing the transition and lowering the effective velocity of the vapor flowing into the interface area. One example, Sulzer MellapakPlus^{TM}, utilizes an "S"-shaped crimp design which gradually increases the packing crimp angle towards the upper and lower edges of the packing element to provide a smooth transition between adjacent packing elements. This is a significant improvement compared to conventional packing design. With this design, flooding no longer starts at the interface of two elements long before the bulk of the packing has reached its limits. The result is a high capacity packing with a useful capacity up to 50% higher than conventional packing at the same efficiency. For conventional packing, a good rule of thumb is that efficiency begins to drop after exceeding a design limit of 3 mbar pressure drop per meter of packing. For high capacity MellapakPlus, this is extended to 5 mbar pressure drop per meter. Figure 3 gives a performance comparison between the conventional packing type Mellapak 250.Y and the corresponding high-performance type MellapakPlus 252.Y.

Table 2 gives an overview and comparison between different packing types. Simulations were performed for a different number of packing types, taking into consideration the efficiency and capacity. Results of

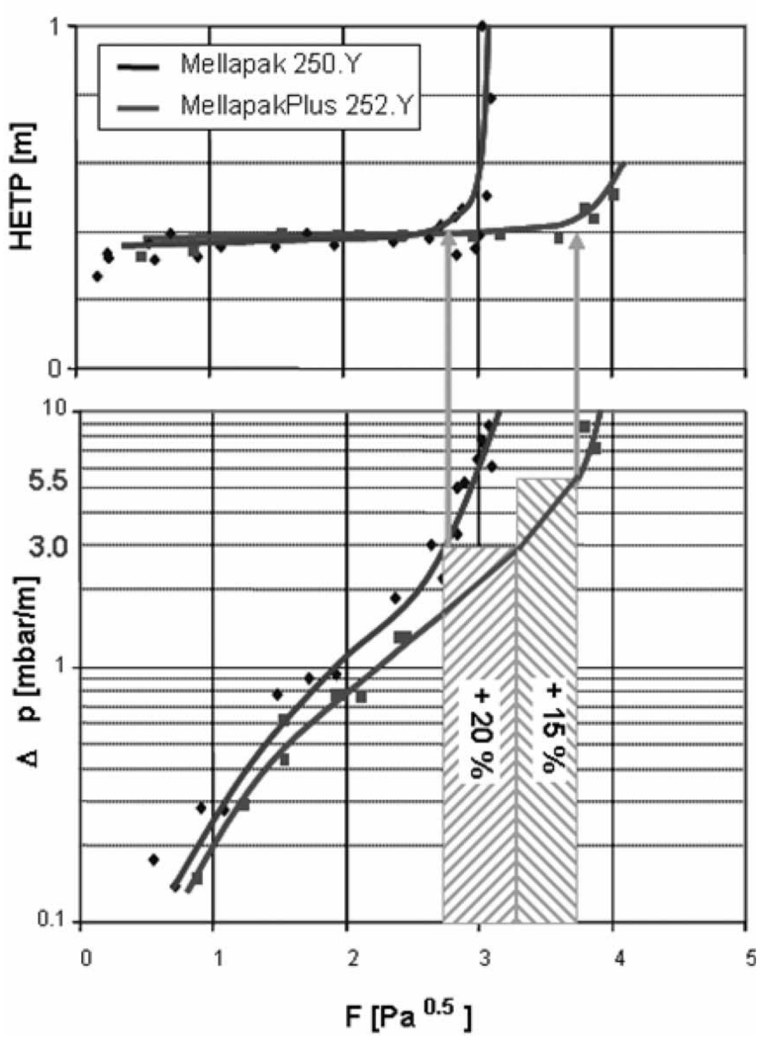


Figure 3. Separation efficiency and pressure drop comparison for conventional packing (Mellapak250Y) and high-efficiency packing (MellapakPlus252Y) (2).

these simulations and a summary for different packing types are presented in Table 3. According to the data presented, the highest energy savings based on steam consumption was provided by MellapakPlus 752Y packing. Because of its higher surface area, MellapakPlus provides the highest possible number of theoretical stages that can be installed within a given column height as compared to MellapakPlus 252Y and 452Y packing. The higher number of stages allows the internal loads and the reboiler duty to be reduced. However, before making any final conclusion,

Table 2. Comparison between available conventional and high-capacity structured packing

Mellapak	NTSM[a] (1/m)	Capacity %	MellapakPlus	NTSM[a] (1/m)	Capacity %
2.Y	2.0	100	202Y	2.0	130
250Y	2.5	100	252Y	2.5	140
350Y	3.5	100	452Y	4.0	130
500Y	4.0	100	452Y	4.0	145
500Y	4.0	100	752Y	5.9	125
750Y	5.9	100	752Y	5.9	140

[a]Number of transfer units per meter of column height

it is always recommended to construct a graph relating the number of theoretical stages versus reflux ratio. As can be seen in Fig. 4, even though MellapakPlus 752 gives the best results from the energy savings point of view, it is close to the operating point of minimum reflux ratio and this should be avoided. The optimum revamp choice for this application is MellapakPlus 452Y. It balances both the energy and capacity requirements of the column. The thermal condition of the feed determines the column energy consumption. A preheater using low pressure steam or another process stream can significantly reduce the column reboiler energy consumption. Additional analyses should be performed to investigate the effect of the feed preheating. Thanks to preheating, the feed can be brought to partial evaporation. Figures 5 and 6 show the results of such analysis. In the first case, the existing feed with a dominant light component was simulated by incremental feed evaporation, while reboiler and condenser duties were evaluated for energy savings. In a second case the same analysis was performed but with the heavy component dominant in the feed, in this case water.

In Case 1, where the feed composition is mainly a light component (methanol), the reboiler duty drops significantly while the condenser duty rises slowly as the feed vapor fraction increases. In Case 2, where the feed consists mainly of the heavy component (water), the reboiler duty drops slowly while condenser duty increases rapidly. The explanation for this effect is that with the lighter feed, the preheating mainly vaporizes the light component and sends it up in the column and the reboiler duty can be diminished. For a heavier feed the preheating vaporizes the heavy component and sends it up the column where it is condensed and redirected to the bottom of the column in order to keep the top product quality (3). Thus, the feed preheat can bring the significant advantage for reboiler energy saving. Final results are presented in Table 4. According to these results, the best solution would be a revamp with high-performance packing like Mellapak452Y, together with the feed preheating.

Table 3. Comparison between existing and different packing type internals

Operating data methanol-water column	Existing internals trays	With Mellapak252Y	With Mellapak452Y	With Mellapak752Y
Feed rate (lb/hr)	22,046	22,046	22,046	22,046
Methanol, bottom (wt%)	0.01	0.01	0.01	0.01
Water, top (wt%)	0.01	0.01	0.01	0.01
Pressure drop (mmHg)	200	9	12	18
Bottom temperature (°F)	227.1	216.6	216.8	216.9
Number of theoretical stages	25	27	34	48
Reflux ratio	1.84	1.59	1.26	1.04
Reboiler duty (MMBTU/hr)	23.68	20	17.3	15.4
Difference (MMBTU/hr)	—	3.68	6.38	8.28
Energy savings (US$) (based on the assumption of 5$/MMBTU and 330 days of operation)		146,000.00	253,000.00	328,000.00

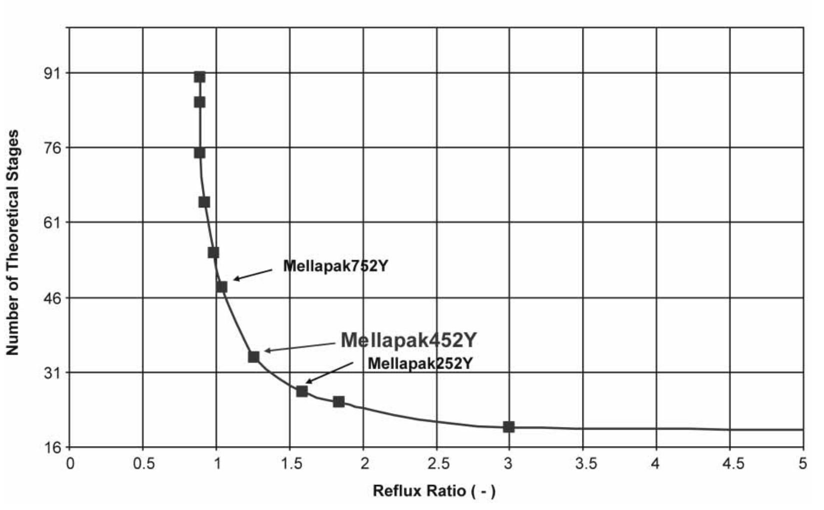


Figure 4. Number of theoretical stages (NTS) as a function of reflux ratio.

Thermal Coupling and Heat Integration between Multiple Columns

Probably the best known arrangement for energy savings in distillation is vapor recompression. It consists of taking the overhead vapors of a column, condensing the vapor to liquid, and using the heat liberated by the condensation to reboil the bottoms liquid from the same column. The temperature driving force needed to force heat to flow from the cooler overhead vapors to the hotter bottoms product liquid is ascertained by either compressing the

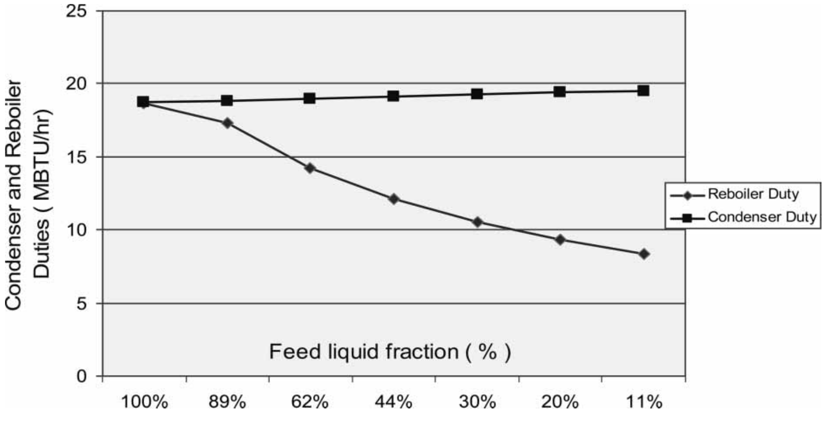


Figure 5. Reboiler and condenser duties as a function of feed thermal state. Case 1–light component dominant in the feed (methanol: 80 wt%, water: 20 wt%).

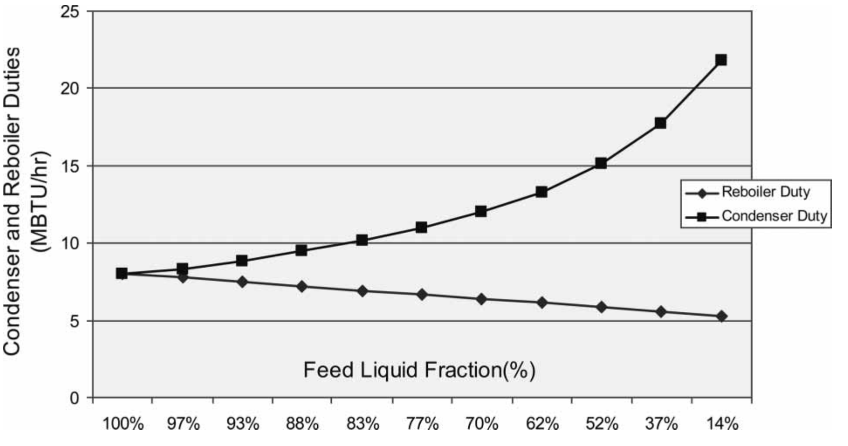


Figure 6. Reboiler and condenser duties as a function of feed thermal state. Case 2–heavy component dominant in the feed (methanol: 20 wt%, water: 80 wt%).

overhead vapor and condense at a higher temperature, or by lowering the pressure on the reboiler liquid to make it boil at a lower temperature and subsequently compressing the bottoms vapor back to the column pressure. Vapor recompression is not suitable for all separation applications. It is attractive for applications involving near-boiling point products and in particular applications with a small temperature differential between the bottom and top of the column.

There are several possible arrangements that utilize two separate towers that are thermally linked. Basically the main principle is to have both of them operating at the different pressure levels. The overhead vapor from the high-pressure tower is used as a heat source to reboil the low-pressure column. A feed can also be split and send to two columns operating in parallel with the same product composition at different pressures. Another configuration is to have columns operating in series, where all the feed enters the high-pressure column. Since the columns operate in series, the top product of the high-pressure column does not have to be on a required purity specification, as it will be processed further in a low-pressure column. The heat integration principle is the same as for a split feed arrangement (4). There are other possible arrangements which are not described here. (e.g., total feed to low-pressure column first, multiple column arrangements, etc.)

As an example, two heat integration configurations are analyzed for a methanol/water system, assuming a feed rate of 110,000 lb/hr. Both high-pressure (HP) and low-pressure (LP) columns have 34 theoretical stages, including condenser and reboiler. In configuration 1, the feed is split between HP and LP columns in a way that HP column gets 45,000 lb/hr of feed and LP column receives the rest of the total feed (55,000 lb/hr). The high-pressure column operates at 50.7 psia overhead pressure, high enough

Table 4. Final design comparison between trays and packing

Operating data methanol-water column	Existing internals trays	With Mellapak252Y	With Mellapak452Y	With Mellapak752Y
Feed rate (lb/hr)	22,046	22,046	22,046	22,046
Methanol, bottom (wt%)	0.01	0.01	0.01	0.01
Water, top (wt%)	0.01	0.01	0.01	0.01
Pressure drop (mmHg)	200	9	12	18
Feed temperature (°F)	176	176	180	176
Number of theoretical stages	25	27	34	48
Reflux ratio	1.84	1.59	1.3	1.04
Reboiler duty (MMBTU/hr)	23.68	20	12.1	15.4
Difference (MMBTU/hr)	—	3.68	11.58	8.28
Energy savings (US$) (based on the assumption of 5$/MMBTU and 330 days of operation)		146,000.00	459,000.00	328,000.00

to get a temperature driving force to heat up the reboiler of the low-pressure column, which operates at sub-atmospheric pressure of 7.2 psia. The column arrangement for this system is represented in Fig. 7, and final results in Table 5. In configuration 2, the full feed goes to the high pressure column, which has an overhead product specification of 3.2 wt% water. The overhead vapor from the high-pressure column reboils the low-pressure column. The condensed vapor is split into a reflux for the high-pressure column and the overhead product, which goes to the low pressure column. The column arrangement for this system is presented in Fig. 8 and final results in Table 6.

Novel Distillation Processes

The Divided-Wall Column concept has been around for a long time. This concept uses a partition wall that physically separates the feed side (prefractionator) and the product side (main column). Compared to the sequencing of conventional columns for separating ternary mixtures, it can save significant amounts of energy by reducing the thermodynamic losses and capital cost investments. However, lack of design experience and fear of operational problems have prevented its widespread use to date (5).

As a general guideline, divided-wall columns can be used when the middle boiling component is in excess in the feed, the desired purity of the middle boiling component is higher than what a simple side-draw column can achieve, and when the product specifications and relative volatility

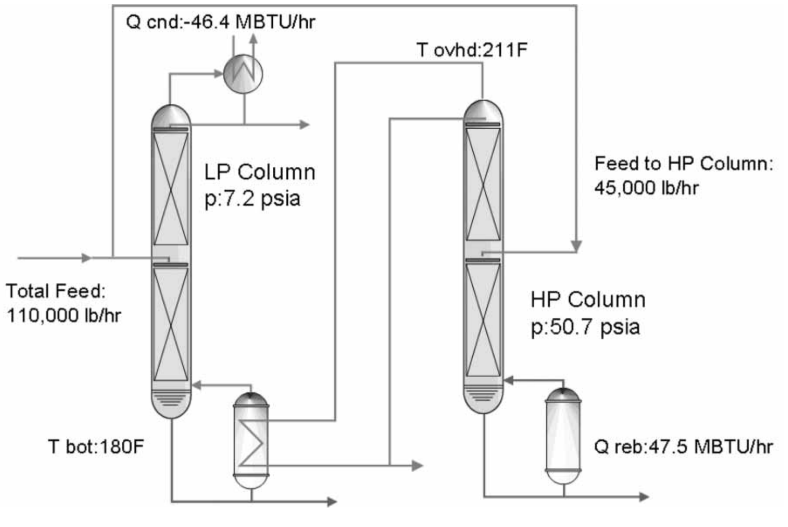


Figure 7. Split-feed arrangement.

Table 5. Split-feed arrangement

Operating data methanol-water column	Single column Mellapak252Y	LP column NEW Mellapak452Y	HP column NEW Mellapak452Y
Feed Rate (lb/hr)	110,000	65,000	45,000
Methanol, bottom (%wt)	0.01	0.01	0.01
Water, top (wt%)	0.01	0.01	0.01
Column app. diameter (ft)	11	8.5	8
Top pressure, psia:	15.95	7.2	50.7
Reboiler duty (MMBTU/hr)	92.4	—	47.5
Condenser duty(MMBTU/hr)	−93.1	−44.26	
Energy savings (US$) (based on the assumption of 5$/MMBTU and 330 days of operation)			1,780,000.00

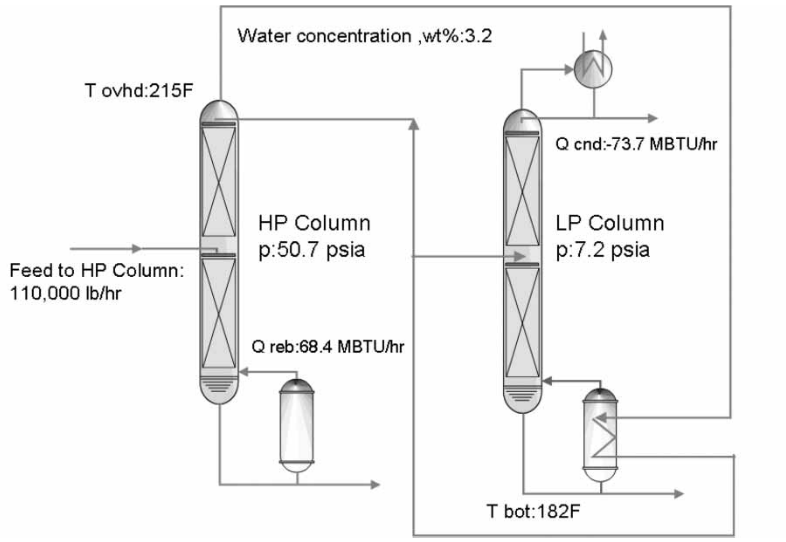


Figure 8. Single-feed arrangement.

distribution is uniform. In general, their use should be avoided when the pressure difference in the conventional sequence is high or if the conventional sequence has large differences in energy consumption between the columns. Thermodynamic inefficiency in the direct separation sequence is manifested in the following way: Consider a mixture of three components A, B, and C (A being the low boiler, C being the heavy boiler, and B intermediate boiling component). In a direct sequence the components will be separated in two distillation columns. The first column separates the lightest component A overhead while the second column separates components B and C. In the first column, the concentration of B builds up to a maximum at the trays near the bottom. On trays below that point, the amount of the heaviest component C continues to increase, diluting B so that its concentration profile now decreases on each additional tray toward the bottom of the column. Energy has been used to separate B to a maximum purity, but because B has not been removed at this point, it is remixed and diluted to the concentration at which it is removed in the bottoms. This remixing effect leads to a thermal inefficiency. On the other hand, the divided-wall column performs a sharp split on the feed side of the column between components A and C, while B is allowed to distribute between these two components. The mixture of A and B is then separated in the top part and overhead product side of the tower while the components B and C are separated in the lower part and bottom product side of the column (Fig. 9).

The ternary system methanol/ethanol/water system has been simulated in a conventional, two-column system as well as in a divided-wall tower to quantify the energy costs difference between these two systems. Process

Table 6. Single feed arrangement

Operating data methanol-water column	Single column Mellapak252Y	LP column NEW Mellapak452Y	HP column NEW Mellapak452Y
Feed rate (lb/hr)	110,000	—	110,000
Methanol, bottom (wt%)	0.01	0.01	0.01
Water, top (wt%)	0.01	0.01	3.2
Column app. diameter (ft)	11	8	10
Top pressure, psia	15.95	7.2	50.7
Reboiler duty (MMBTU/hr)	92.4	—	66.7
Condenser duty(MMBTU/hr)	−93.1	−73.7	
Energy savings (US$) (based on the assumption of 5$/MMBTU and 330 days of operation)			1,020,000.00

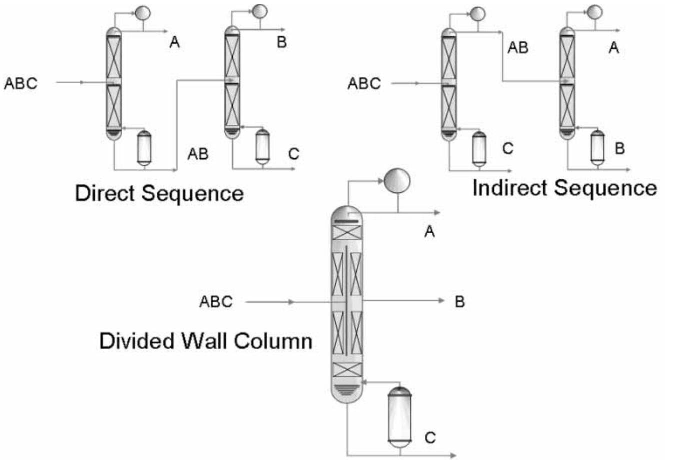


Figure 9. Divided wall concept.

conditions and required product purities are presented in Table 7 while the summary of the results comparing the direct sequence of separating this mixture in a conventional distillation system and in a divided wall column are presented in Table 8. As shown, the overall energy savings are between 25% and 30%. So divided-wall columns should be considered wherever possible to achieve the full economical and cost reduction benefits.

Hybrid Systems with Distillation and Pervaporation

Pervaporation is a membrane process for separating mixtures of volatile components. It enables solvents to be dehydrated without using a third substance or entrainer. Azeotropes can be dehydrated simply, cheaply and

Table 7. Process conditions—methanol/ethanol/water separation

Feed flow rate, lb/hr	110,000
Feed temperature, °F	149
Feed pressure, psia	18.8
Methanol in feed, wt%	20
Ethanol in feed, wt%	55
Water in feed, wt%	25
Column operating pressure, psia	14.5
Product purity, methanol, wt%	95
Product purity, ethanol, wt%	93
Product purity, water, wt%	99

Table 8. Design comparison—conventional sequence versus divided wall column

	Condenser duty, MMBTU/hr	Reboiler duty, MMBTU/hr	Refux ratio
Column 1	113.89	111.9	8.9
Column 2	115.9	112.64	2.8
Total	229.79	224.54	
Divided-wall column	167	170	13.6
Difference	63	54.54	
Savings (Based on the assumption of 5$/MMBTU and 330 days of operation)		2,160,000.00	

without problems irrespective of vapor-liquid equilibrium. Main features of pervaporation are:

- Tailored non-porous membranes which selectively permeate one or more components.
- Maximum driving force provided by applying vacuum on the back side of the membranes, thus allowing almost complete removal of the permeating component.
- The permeating component leaves as a vapor.
- Separation is predominantly driven by polarity difference–polar components permeate faster through hydrophilic membranes.
- Feed can be liquid (pervaporation) or saturated vapor (vapor permeation).

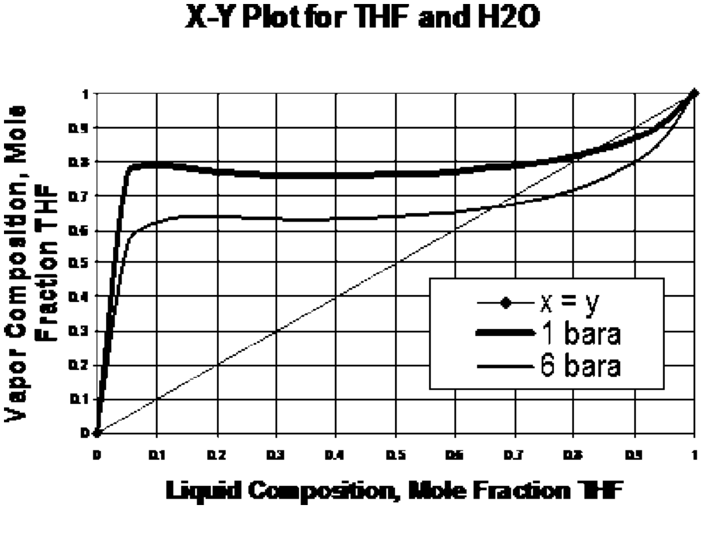


Figure 10. THF – Water system equilibrium diagram.

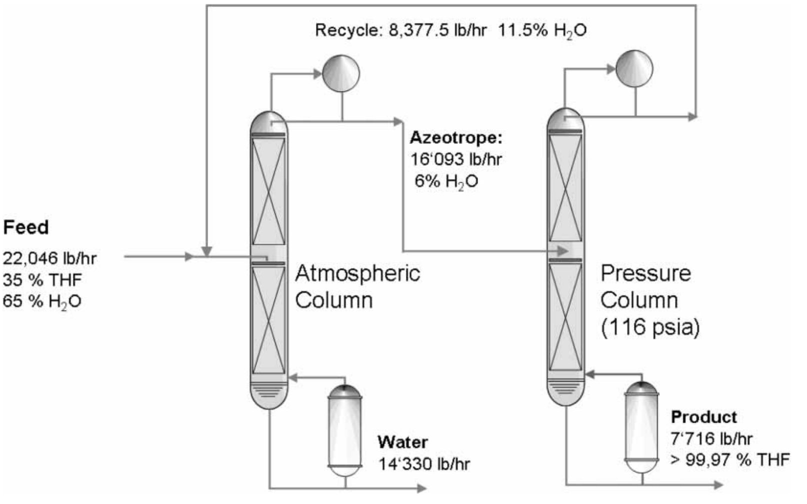


Figure 11. THF–Water separation using pressure swing distillation (PSD).

The distillation process is driven by a volatility difference. If volatility differences are small, or become small under certain conditions, columns need to operate with high reflux to achieve the desired separation. Pervaporation can be used to debottleneck distillation columns or can be used together with distillation to break azeotropes.

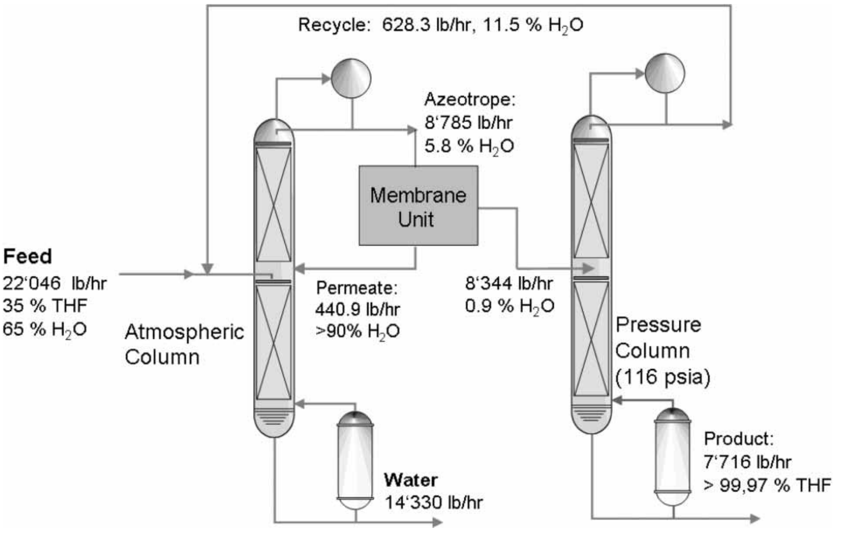


Figure 12. THF-Water separation using distillation/pervaporation hybrid system.

The THF (tetrahydrofurane)—water system has an azeotrope which can be shifted substantially by changing the system pressure. A THF-water mixture forms a binary minimum azeotrope which shifts towards the low-boiling component, THF, at lower system pressure. The binary azeotrope can be broken by first separating the high boiler at atmospheric pressure (water) and subsequently the high boiler at elevated pressure (THF). The composition of the overhead stream of the atmospheric column should be as close as possible to that of the azeotrope. After the atmospheric column, the azeotropic mixture is fed to the second, high-pressure column. Because the azeotrope forms at a lower THF concentration at the higher pressure, the THF can be removed as a pure bottom product from this column. This dual-column arrangement is sometimes called a Two-Pressure Distillation (TPD).

The vapor-liquid equilibrium curve for THF-water is shown in Fig. 10. The process flow diagram for separating the THF-Water mixture using the TPD approach is presented in Fig. 11. The main problem is in the large stream that has to be recycled to the atmospheric column, which leads to an increase of the physical size of the column and thermal requirements. This can be resolved by placing a pervaporation unit to treat the THF-water azeotrope coming out of the atmospheric tower and separating the feed into a water-rich permeate and THF-rich retentate that is fed to the high-

Table 9. THF–water separation comparison—values for production of 67,730 lb/yr of >99.97 wt% THF

Steam 58 psia	MBTU/hr	t/hr
Without PV		
Reboiler T-1	6.7	3.01
Reboiler T-2	4.16	2.05
Total steam	10.86	5.06
With PV		
Reboiler T-1	4.0	1.99
Reboiler T-2	1.0	0.51
PV Stage	0.68	0.34
Total steam	5.68	2.84
Cooling water 10°C Δ T	MMBTU/hr	m3/hr
Cond. T-1	4.5	114
Cond. T-2.	3.1	78
Total CW	7.6	192
Cond. T-1	1.98	50
Cond. T-2.	0.71	18
Perm. Cond.	0.47	12
Total CW	3.16	80

Table 10. Summary for different separation configurations

Configuration	Improvement/Advantage	Disadvantage
Existing column configuration internals: trays or packing	• Correct Feed Plate Location will improve column efficiency and lower steam consumption • Feed thermal state (subcooled, bubble point or superheated) can decrease column loads and reduce the energy consumption	• Increased capital cost • Not always possible to modify a feed location
Conventional distillation column revamp using structured packing	• Higher mass-transfer efficiency than trays leads to reduced vapor/liquid loads and reduced reboiler and condenser duties • Packing pressure drop is much lower than trays; pressure drop reduction can translate into a capacity gain • Low liquid holdup features less residence-time-related degradation of the product	• Less flexibility of feed location because liquid draw-off and feed can only take place between beds • The separation efficiency for structured packing diminished at high pressure and high liquid load (in general at operating pressures over 100 psi)
Double- or multi–effect distillation systems	• Double-effect systems can save roughly half the energy compared to conventional systems • In situations when existing column shells can be revamped with high-capacity structured packing, savings on column shells are substantial • Less capital investment as heat pumps system, especially for vacuum service, because it avoids the use of a compressor.	• Involves a large capital investment and has to be justified with the cost of energy • System control more challenging • Multi-effect distillation increases the operating temperature range for the separation

(*continued*)

Table 10. Continued

Configuration	Improvement/Advantage	Disadvantage
Heat pump technology/vapor recompression	• Enable the use of the condensation energy for the service of the reboiler with a small work input • No need for vapor, which also means saving on steam production unit • The greater the reboiler/condenser duties, the more attractive the heat pump is • Minimized pressure drop translates into small compression ratio requirement and reduction in compression capital and energy costs	• Disadvantage when fractionation system has a high temperature difference along the column • Some products are difficult to compress without risk of polymerization in direct heat pump application (in that case the indirect heat pump is favored) • High capital cost
Thermally coupled columns (divided wall column)	• Low capital cost by integrating the pre-fractionator and main column in one shell • DWC system requires only one condenser/reboiler compared to two column system • Less plot plan for a grass roots plant • Low energy cost (no remixing) • The purity of the middle product is greater than can be achieved in a simple sidedraw column	• Middle boiling component should be in excess and the required concentration not too pure. • When the A/B split is easy relative to B/C split, the DWC advantage may not be great enough • DWC is not an option when two columns in direct/indirect sequence require different operating pressures

Membrane systems hybrid pervaporation/distillation systems	• Azeotrope breaking and production of relatively pure material • Ideal for small to moderate feed rates • Can be optimally combined with distillation equipment • Vapor permeation requires does not require energy input. • No solvents or entrainers are used to break the azeotrope	• Driving forces for permeation are low, requiring large membrane surface area. However, if PV used to "jump" azeotrope only and there is no requirement for a pure product, the driving force is high and membrane area low • Limitation if the solid material is present in feed (only in case of pervaporation; solids not a problem for vapor permeation)

pressure column. With this configuration, the recycle stream becomes much smaller and energy savings are substantial. The process flow diagram of the combined distillation-pervaporation system is presented in Fig. 12 and an energy savings comparison in Table 9.

SUMMARY

In the past, for large distillation systems, despite the fact that they were not energy efficient and required substantial amounts of steam, the capital costs were considered to be of higher importance than the energy costs. However, this has changed substantially, mainly due to high fuel and related energy costs. Also, new technologies and advanced distillation systems established their position in the market and proved themselves as a reliable and safe to operate. Even though distillation will remain the leading separation process for the foreseeable future, optimization or combination with other technologies can bring significant economic benefits. Table 10 provides a summary of different configurations, including the advantages of each, as well as their disadvantages.

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