Be Smart about Column Design

Mark Pilling, P.E.
Daniel R. Summers, P.E.
Sulzer Chemtech USA

Optimizing distillation equipment and processes can improve both the profitability and the greenness of an operation.

Chemical plants consume large amounts of energy, much of which goes into separations, particularly distillation. Distillation columns also typically process significant quantities of feedstock to produce high volumes of finished products with (ideally) a minimal amount of waste. High energy consumption combined with large processing volumes makes the distillation process a prime target for optimization.

One approach to optimizing distillation is to design "green" columns. A more-effective approach, however, and one that is discussed in this article, is to build columns with "smart" designs.

In essence, the principles of green design are simple: Use materials wisely, conserve water and energy, save money in the long term, and create surroundings that are safe and healthy. In other words, follow the standards of good engineering *(1)*. This certainly applies to distillation, although perhaps it could be better stated as good engineering design with a continual emphasis on green principles. This is what is meant by the term *smart design.*

In this article, smart design refers to approaches that use minimal resources over the life of the process and that are also safe and environmentally sound. Resources (which are also referred to as embodied energy), in turn, consist of materials, feedstocks, energy, effort, etc.

Table 1. Assumptions simplify the analysis of smart column designs.

Assumption	Consequence for Scope
Production of the various chemicals from the various feedstocks is mandatory	Reduction of product quantities will not be considered
The process of converting a certain feedstock into a certain product is the most effective way possible	Process optimization or alteration outside of the distillation area will not be considered
Distillation is the most effective means of separation for producing the final product	Processes other than distillation will not be considered

Scope and boundaries

To keep the scope of this topic manageable, we make three important assumptions, which along with the resulting consequences are listed in Table 1. All of these assumptions, to some extent, are incorrect, especially the first one. Most, if not all, users of chemical-based products could get by with less. As for the second and third assumptions, many bright chemical engineers are currently working to prove them incorrect. Regardless of their accuracy, these assumptions create a simpler engineering system in which the impact of distillation column design can be isolated.

This article focuses on the distillation columns themselves and the process and equipment immediately surrounding them. The design of this system is considered in three stages, which are represented by the concentric circles in Figure 1. The outer boundary of the design considers the cradle-to-grave resources consumed by the system, from column construction through the lifespan of the equipment. The boundaries narrow as the design progresses.

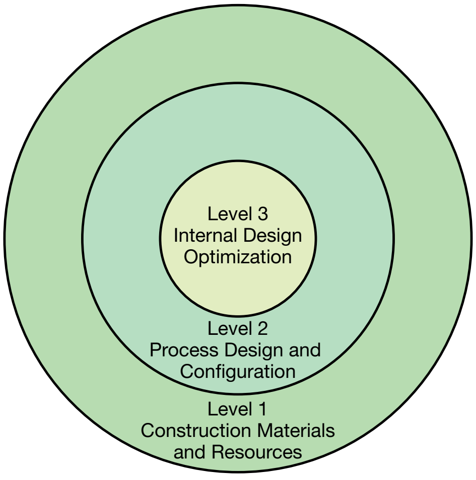
Column sizing

Column sizing is a fundamental aspect of column design. The size of a column is determined by capacity and efficiency requirements.

To achieve the necessary heat and mass transfer, the vapor and liquid streams must continually mix and separate throughout the column. Capacity is set by the allowable vapor and liquid velocities flowing through the column. Within a horizontal cross-section of the column, there must be adequate space for the vapor to flow upward and for the liquid to flow counter-currently downward.

Based on the physical properties of the fluids, there is a limit to how much flow can be processed within a column. Fractionation Research, Inc. (FRI) refers to this as the system limit, which is used to calculate the maximum capacity of a column regardless of the internals *(2)*. The calculation is based on Stokes' Law, and is used to predict the vapor velocity at which a liquid droplet of a specific size can no longer travel downward through that vapor stream. This provides a practical limit for sizing columns with respect to diameter.

The design of a column and its internals typically involves a tradeoff between capacity and efficiency. Take structured packing as an example. A structured packing with a low surface area (*e.g.,* 125 m^2/m^3) provides high capacity and low efficiency; a column with this packing can be smaller in diameter, but to achieve the required number of stages must be taller than a column whose packing has a much higher surface area (*e.g.,* 750 m^2/m^3). A high-surface-area packing provides less capacity but more efficiency, allowing the column to be shorter, but requiring a larger diameter. Either column can achieve the same throughput and the same separation, provided the column geometry and internals are properly matched.



▲ **Figure 1.** Concentric circles characterize the narrowing scope of the design process.

◤ **Figure 2.** Bubble cap trays require a large amount of metal.

Level 1: Construction materials and resources

Column materials. To minimize capital costs, columns are typically constructed with the smallest diameter and lowest height practical. (Gone are the days when columns were designed with large amounts of extra capacity.) This does not mean, however, that the very smallest column possible with the highest-performance internals should be selected for a grass-roots application with more than a minimal life expectancy. Unless there is no reasonable chance the design will be modified in the future, some degree of operational freedom should be factored into the sizing process.

Column internals, both trays and packings, are made as thin as is practical to meet the necessary mechanical requirements. Great care is taken to minimize the quantity of raw materials used to construct the distillation equipment. During manufacturing, virtually all unused material is collected and recycled as scrap.

Until the 1950s, bubble cap trays (Figure 2) were used for systems with high turndown. The fabrication of bubble cap trays requires a large amount of metal, and their installation requires a significant amount of labor.

In 1960, Earl Nutter developed moving round valves (Figure 3) on a tray deck as a more cost-effective alternative to bubble cap trays. These new trays require considerably less material for their construction *(3)*.

The moving-valve design evolved to rectangular valves

▶ **Figure 3.** Round valves require less material than bubble caps.

▲ **Figure 4.** Rectangular valves can be manufactured with little to no scrap.

◀ **Figure 5.** Fixed valves are formed from the tray deck.

(Figure 4). A substantial amount of scrap is generated during the manufacture of round valves, in large part because of their radially extending legs. In contrast, rectangular valves are easily formed from a rectangular sheet with little to no scrap. Thus, rectangular valves are a smarter, more cost-effective solution.

Today, many tray designs use fixed valves, such as the one shown in Figure 5. These trays offer better performance than a conventional sieve or valve tray because the valves are formed out of the tray deck itself. No additional metal is added to the tray and no scrap metal is lost, making this the greenest design from a materials standpoint.

These examples demonstrate that, as designs evolve over time, good engineering generally improves both performance and cost-effectiveness.

Equipment lifespan. Most internals are designed for a relatively long life, typically in excess of 20 years. Therefore, selection of the proper metallurgy is vital. Structured packing that is 0.10 mm thick with process exposure on both sides is too thin to be designed with a corrosion allowance.

Column internals removed after their useful life are typically collected, cleaned as necessary, and sent for scrap recycling. Since column sizes and loads are essentially unique, reuse of internals for different columns is extremely rare (although reuse of the columns themselves is not).

Equipment manufacturers, engineering companies, and operators do everything practical to use as little material as possible over a lifespan that is as long as possible.

Level 2: Process design and configuration

During process design, two major points of focus are obtaining the greatest valuable yield from the column as a percentage of feed, and doing this with the least amount of energy. On the process side, this can entail sequencing of multiple columns, as well as modifying the process configuration itself (*e.g.,* feed/effluent exchanger systems, reboiler and condenser heat-transfer media, reboiler and condenser configurations, optimization of the number of stages vs. duty, divided-wall columns, and optimized control strategies).

Column sequencing. When multiple separations and/or columns are required, column sequencing is an excellent method to minimize the number of column vessels and energy consumption. Energy savings as high as 48% have been reported *(4).*

For a given set of required separations, the number of sequencing possibilities increases exponentially with the number of product streams. For example, four streams can be arranged in 18 different configurations if no thermal coupling is considered. For a five-component system, the number of possible configurations increases to 203. When thermal coupling is considered, this number increases to nearly 6,000.

Among these configurations is one that requires the minimum expenditure of resources. A process engineer today has the methodology and computing power required to find that ideal configuration during the conceptual phase of the project. These methods should be used in the design of any moderate to highly complex column series.

Advanced controls. Advanced process controls provide many benefits. The goal of most advanced control schemes is to achieve the desired product rate and purity while using the least amount of resources, namely feed and energy. By definition, these are smart designs.

Adjustable cutpoint control allows operations to be adjusted in response to changing economic drivers and production to be shifted from lower-value products to higher-value ones. Feed-forward control analyzes the feed composition upstream of the column and adjusts column operations to more quickly respond to operational swings or startup sequences. This helps to stabilize column operation, hopefully eliminating off-spec products and minimizing energy input into the column.

Floodpoint control is another advanced control tool that has proven to be beneficial. Once a column goes into a flood condition, pressure drop can increase substantially and product quality can degrade significantly. Columns typically have specific operational precursors to flood that can be detected and monitored. This information can be used to adjust column operation so that it can effectively run near the flood point without experiencing the erratic behavior or off-spec products associated with flooding conditions *(5).*

By using the appropriate control instrumentation and logic, column capacity can be increased and/or energy consumption can be reduced for highly loaded applications. This produces the maximum amount of throughput with the lowest possible resource consumption.

Heat integration. A column should be appropriately heat-integrated into the process using methods such as pinch analysis. Processes that can use lower-level sources of heat or preheat configurations such as feed/bottoms exchangers are desired, as long as operational efficiency and capital expenses are not adversely affected.

A good example of this is side reboilers. Since they operate at a lower temperature than a reboiler, they can use a cooler heat source than the reboiler, such as a product stream headed for storage. This pairing serves two beneficial purposes — it provides heat to the column, and it reduces or eliminates some of the cooling duty that would otherwise be required for that product stream.

Refinery crude preheat trains are another good example of heat integration. They utilize several large banks of feed exchangers that heat the incoming crude prior to distillation while cooling the hot product streams headed to storage.

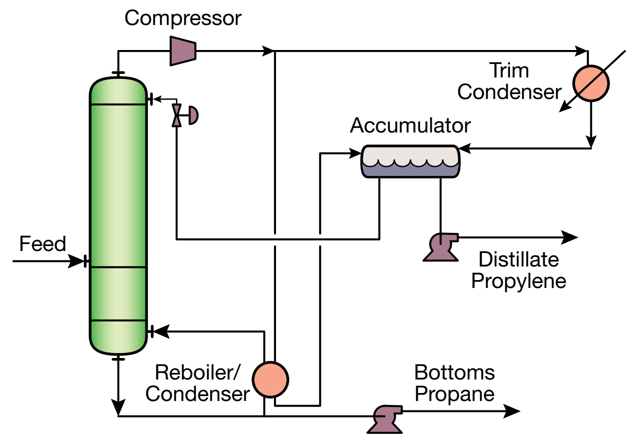
When making these modifications, designers must ensure that the exchangers and alternative heating sources are adequate for startup conditions and alternative feed source conditions.

Heat pumps. Significant energy savings — up to 90% — can be obtained by compressing the overhead vapor from a distillation tower to a temperature (and pressure) sufficiently higher than the tower's bottom temperature and using that heat in the column's reboiler. For a heat pump application to be successful, the difference between the top and bottom temperatures of the tower should be no more than about 25°F. In addition, the bottom liquid's heat of vaporization and the overhead vapor's heat of condensation ideally should be very close and the pressure drop across the column internals should be less than about 15 psi. Separations involving compounds with low relative volatilities are ideal candidates for vapor-recompression type heat pumps.

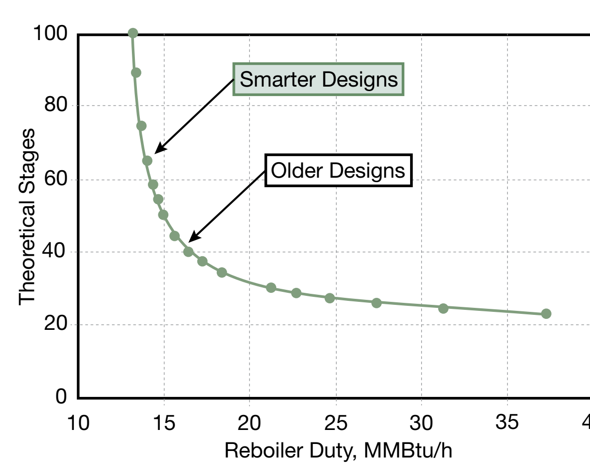
C_3 splitters are frequently designed with vapor-recompression heat pumps when sufficient low-energy heat sources (*e.g.,* steam condensate or waste steam let down from a high-pressure steam user) are not available. A typical flow scheme is shown in Figure 6. The heats of vaporization of propylene (the overhead product) and propane (the bottoms product) at 100 psi are nearly identical (157.6 and 151.7 Btu/lb, respectively). The only energy needed for a C_3 splitter heat pump is the compressor duty, which is typically only 11–12% of the total reboiler duty. Therefore, the energy savings are significant.

In addition, C_3 splitter heat pump systems operate at much lower pressures than conventional columns without heat pumping. The high-pressure compressor discharge stream is cooled with cooling water, so the compressor discharge is the same as the conventional tower's top pressure. Since single-wheel compressors typically have a compression ratio of 1.8:1, the operating pressure of the heat-pumped C_3 splitter column is 56% (1/1.8) of the conventional C_3 splitter pressure. With a lower operating pressure, the required thickness of the pressure vessel walls is lower, which provides a capital cost savings. The lower pressure also results in a higher relative volatility, so fewer theoretical stages are required to achieve the separation. This translates to fewer trays and a shorter column. The result is a smaller column that uses significantly less materials and energy.

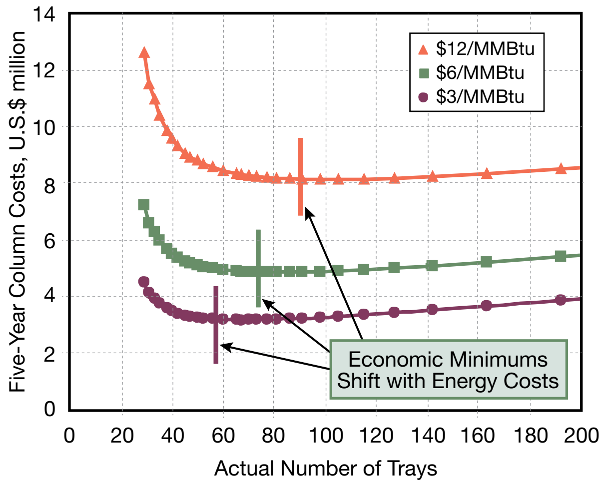
Stages vs. duty. A review of stages vs. energy (or column height vs. column diameter) is an integral part of the column design and configuration process. An example of the relationship between reboiler stages and duty is shown in Figure 7. Reboiler duty decreases as the number of stages



▲ **Figure 6.** A C_3 splitter with a vapor-recompression heat pump is smaller and consumes much less energy than a conventional C_3 splitter.



▲ **Figure 7.** A stages vs. duty curve depicts the trade-off between capital (stages) and operating (energy duty) costs.



▲ **Figure 8.** The optimum stages-vs.-duty design point is a function of the price of energy.

increases. In the past, columns were typically designed somewhere around the focus point of the hyperbola to minimize sensitivity to process changes and maximize design and operational flexibility. In this case, that would be at approximately 40 theoretical stages with an expected reboiler duty of 16.5 MMBtu/h. A greener column, however, might be designed with 50 stages to reduce energy consumption by about 10%, or even with 60 stages to obtain a 15% reduction in energy duty.

The price of energy influences the optimum stages-vs.-duty design point. The best solution can usually be obtained by assuming higher energy costs, thereby minimizing energy consumption.

Figure 8 presents an evaluation of total column capital and operating costs as a function of energy costs. For this particular design, at an energy cost of $3/MMBtu, the optimum number of actual trays is just fewer than 60. However, if energy costs double, the optimum design becomes approximately 75 trays. If energy costs double again, the optimum tray count increases to 90. Clearly, at some point, it is no longer cost-effective to add more trays, but this diagram does show that many column designs may be far from the optimal number of stages when they are analyzed from an energy perspective.

Divided-wall columns. Divided-wall column designs can be used when there is an excess of the middle-boiling component and the split between the light and middle components is at least as difficult as the split between the middle and heavy components. These columns have traditionally been packed, but many good trayed designs exist as well. Whether trayed or packed, a divided-wall column's capital and energy costs can be as much as 30% lower than those of conventional designs.

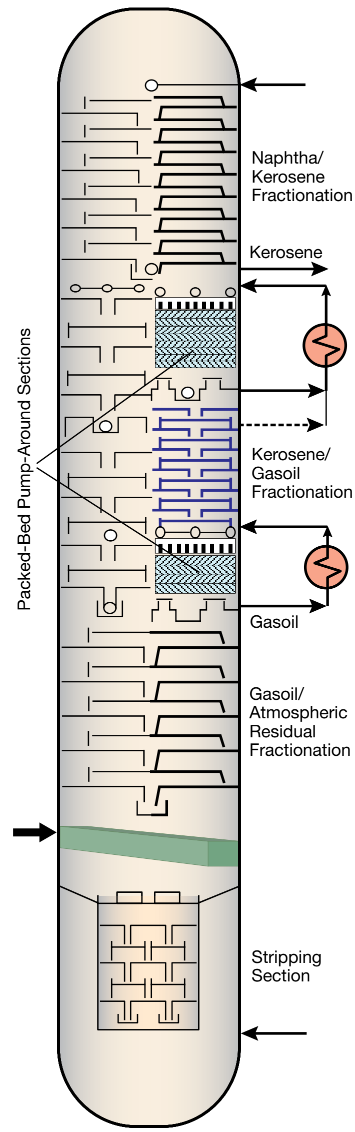
Table 2 compares mass balances and energy requirements for a conventional column and a divided-wall column for a benzene-toluene-xylene (BTX) separation *(6)*. For this particular separation, the divided-wall column's energy consumption of 80.2 MMBtu/h is 28% lower than the 112.1 MMBtu/h energy consumption of the conventional design.

Level 3: Internal design and optimization

The physical and transport properties of column internals have a large influence on the column's efficiency. In services where the process characteristics favor high efficiency (*e.g.,* moderate-pressure distillation columns, such as debutanizers

Table 2. Material balances for a conventional and a divided-wall BTX column.

Component	Feed	Conventional			Divided-Wall		
		Benzene	Toluene	Xylenes	Benzene	Toluene	Xylenes
Hexane and lighter	8.87	42.30	0	0	42.29	0	0
Benzene	7.82	37.25	0.02	0	37.08	0.15	0
Heptane	3.47	14.45	1.54	0	14.6	1.4	0
Methyl cyclohexane	0.15	0.22	0.35	0	0.245	0.34	0
Toluene	30.28	5.66	94.56	4.16	5.66	94.56	4.16
2-Methyl heptane	1.0	0.12	3.32	0.06	0.13	3.34	0.05
Ethylbenzene	5.38	0	0.11	10.62	0	0.1	10.63
p-Xylene	5.67	0	0.04	11.21	0	0.04	11.11
m-Xylene	12.0	0	0.06	23.76	0	0.05	23.78
o-Xylene	7.44	0	0	14.74	0	0	14.74
Trimethyl benzene and higher	17.92	0	0	35.46	0	0	35.53
Total Reboiler Duty		112.1 MMBtu/h			80.2 MMBtu/h		



▲ **Figure 9.** Increasing the number of trays by decreasing the tray-to-tray spacing can increase capacity and reduce energy consumption. Courtesy of Stefano Costanzo.

and depropanizers), either a well-designed tray set or a well-designed packed bed can achieve relatively good efficiency. In naturally low-efficiency systems (*e.g.,* high-relative-volatility separations, such as strippers and absorbers), both trays and packings have lower-than-average efficiencies, regardless of how well designed they are.

You can, however, take steps to maximize the efficiency of whichever column internals you choose, to get the most out of what you have available. This is the essence of a smart design.

Packings. Packing designs have significantly fewer degrees of freedom than tray designs. The engineer must first choose the packing type that is best for the particular process, and then determine the packing size that optimizes the bed height vs. the column diameter. After the packing type and size have been selected, the design focus typically shifts to the liquid distributor. Although the ideal liquid distributor cannot significantly improve packing performance, a poorly designed or poorly functioning distributor can certainly make performance dramatically worse. Spending a little extra time confirming that the distributor design is appropriate for the feed and the packing type is usually a wise choice.

Trays. For trays, the number of variables that can be changed or adjusted is seemingly infinite. Furthermore, in many cases, one design is optimal for one set of possible operating conditions, while another set of conditions has a different optimal design.

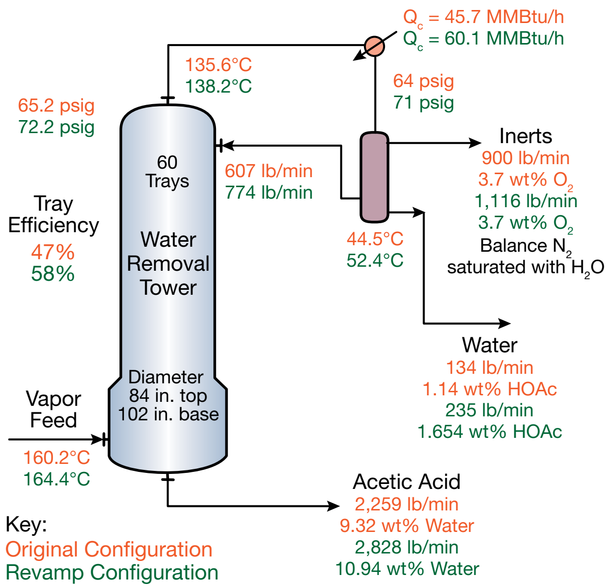
Thus, designers must determine how much of the time the column will operate under various conditions. They often then create one tray design for the most prevalent operating scenario and install that design in the tower; if the operating conditions change significantly, the plant completely changes out the trays.

A better alternative might be to supply a single tray design that can perform reliably at various rates and under variable conditions. This may require slightly larger tray spacings or a larger tower diameter to accommodate the wider operating range. Although this may not be the most economical short-term solution, reductions in unit downtime, materials, and overall energy consumption could make it the smartest choice.

Tray efficiency is affected by vapor and liquid diffusivities and contact time. Diffusivities are mainly affected by pressure, temperature, and viscosity. Ordinarily, diffusivities are not measured or reliably calculated, so more-common variables (*e.g.,* liquid viscosity, relative volatility, surface tension) are used to predict diffusivities which, in turn, are used to predict a system efficiency. This system efficiency represents the efficiency that can be expected with a standard internal design. Engineers then have the interesting task of identifying changes to the tray design that could enhance efficiency beyond that. Some of these methods are discussed in the following paragraphs.

Tray spacing. The simplest way to gain efficiency is to increase the number of trays within a given section by reducing the spacing between trays. For instance, a 4-for-3 tray revamp (*e.g.,* replacing 18 trays on 24-in. spacings with 24 trays on 18-in. spacings) increases the number of theoretical stages (NTS) of a section by 33%. Since capacity decreases with lower tray spacing, higher-performance (*i.e.,* higher-capacity) trays are usually needed to handle the capacity while delivering the same (or nearly the same) tray efficiency per tray.

In one column revamp project, conventional trays were replaced with high-performance (HP) trays on lower tray spacings in the fractionation section and with new packed beds in the pump-around (PA) sections (Figure 9). These



▲ **Figure 10.** Push valves improved the efficiency of the trays in an acetic acid tower.

modifications increased column capacity by 10% and reduced energy consumption by 14%. This is another demonstration of the green principle of getting more with less.

Flow path length. Another important tray design variable is flow path length, *i.e.,* the distance the liquid flows horizontally across the tray. Tray efficiency typically increases with increasing flow path length. For example, if a 600-mm flow path length design is varied by 100 mm in either direction, the longer flow path will have a higher efficiency and the shorter flow path will have a lower efficiency. Keep in mind, though, that efficiency is not a linear function of flow path length — *i.e.,* doubling the flow path length does not double the tray efficiency.

The minimum allowable mechanical flow path length (below which a tray panel can no longer be installed due to space constraints) is somewhere around 350 mm. The practical maximum flow path length is around 2 m, assuming that the design provides uniform liquid distribution, minimal backmixing of liquid on the tray deck, and no susceptibility to vapor crossflow channeling. Flow path lengths longer than 2 m provide no better efficiency.

Push valves are a good option for trays with flow paths longer than 1.5 m. Push valves help to maintain a steady liquid flow across the tray deck because they counteract the tendency of trays to experience retrograde liquid flow toward the sides of the flow path. In one project *(7),* revamping a 2.13-m-dia. acetic acid tower with push valves increased the measured tray efficiency by 23% (Figure 10).

Trays using push valves exclusively have excellent capacity but reduced efficiency due to the extensive pushing of the valves. As a general rule, medium- to larger-diameter trayed columns (above 2 m) can often benefit from the addition of push valves among the standard valve types.

Closing thoughts

Smart column design is primarily a function of understanding the process requirements and then using good process design. Green designs are smart, cost-effective solutions. There are almost limitless opportunities available to improve a column design. A good engineer looks for all of them and then uses those options that make the most sense for that particular application. ◆

Literature Cited

1. **Gorman, J.,** "The Best of Green Design: Overview," *Popular Mechanics,* www.popularmechanics.com/science/environment/4212653 (Oct. 1, 2009).
2. **Chen, G. X.,** "System Limit Capacity of Fractionators," Topical Report 136, Fractionation Research, Inc., Stillwater, OK (Jan. 2000).
3. **Nutter, I. E.,** "Valve Mechanism for Fluid and Liquid Contact Apparatus," U.S. Patent 3,287,004 (Nov. 1966).
4. **Shah, V. H., and R. Agrawal,** "A Matrix Method for Multicomponent Distillation Sequences," *AIChE Journal,* **56,** pp. 1759–1775 (2010).
5. **Dzyacky, G., *et al.,*** "Increasing Distillation Column Throughput," *Petroleum Technology Quarterly,* pp. 99–104 (Q4 2005).
6. **Summers, D. R.,** "Push Valve Experience on Distillation Trays," Distillation 2005, Topical Conference Proceedings, AIChE Spring Meeting (Apr. 2005).
7. **Summers, D. R.,** "Divided Wall Columns —Tray Technology," presented at the 3rd AIChE Regional Process Technology Conference, Galveston, TX (Oct. 6, 2011).

MARK PILLING, P.E., is the Manager of Technology for Sulzer Chemtech USA (Email: mark.pilling@sulzer.com), where he oversees the development of mass-transfer equipment and specializes in applications for various process technologies. Within Sulzer, he is responsible for leading tray research and development projects and is the packing product manager for North and South America. He is an active member of Fractionation Research, Inc. (FRI), where he serves as vice chair of the Technical Committee and chair of the Long-Range Planning Committee. A Fellow of AIChE, he served as a director of the Separations Div. from 2005 to 2009 and is is currently chair of the Separations Div. A registered professional engineer in Oklahoma, he holds a BS in chemical engineering from the Univ. of Oklahoma. He holds several patents related to distillation tray technology.

DANIEL R. SUMMERS, P.E., is the Tray Technology Manager for Sulzer Chemtech, USA. He started his career in Union Carbide's Separations Design Group, and has worked for Praxair, UOP, Stone & Webster Engineering, and Nutter Engineering. For the past 35 years, he has been involved in the development, design, operation, and troubleshooting of all forms of tower internals in the hydrocarbon, specialty chemical, refining, air separation, and natural gas industries. His specialty is high-capacity tray devices. He is chair of FRI's Design Practices Committee and co-chair of AIChE's Tower Internals Testing Procedure rewrite committee, and is the author of 49 papers on distillation and a listed inventor on two U.S. patents. He holds a BS in chemical engineering from the State Univ. of New York, Buffalo, and is a registered professional engineer in New York and Oklahoma. A Fellow of AIChE, he has been a member of AIChE since graduation and of AIChE's Separations Div. since its formation.