THE INTEGRATION OF ENERGY CONSERVATION PRINCIPLES INTO A COURSE ON STAGED OPERATIONS

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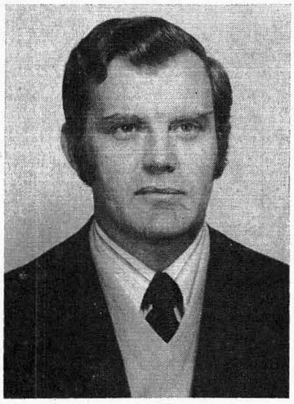
MY INTERESTS IN ENERGY conservation began with a one credit special topics course which involved studying our local ice rink to suggest energy conservation measures [8]. The course was very successful and student enthusiasm was high. The motivating factors were that we were working on a real system, we had to define the problem, and that energy conservation was topical. After the course the Department of Energy awarded a contract to develop the class' results into a technology transfer manual which was recently published [1].

The Department of Energy's technology transfer series covers a wide range of topics such as energy conservation in distillation, evaporation, and the use of computers for energy conservation. Staged operations in general and distillation in particular are prime areas for energy conservation. It has been reported [9] that 3% of the energy used in the United States goes into distillation. When I taught our senior course on staged operations I decided to integrate energy conservation into the course. About 25% to 30% of the course involved energy conservation. Again student interest and enthusiasm were very high.



Thomas McAvoy received his B.S. in Chemical Engineering from Brooklyn Polytechnic Institute in 1961. His M.A. (1963) and Ph.D. (1964) degrees in chemical engineering were obtained from Princeton. He has taught for 17 years and recently joined the University of Maryland. He has carried out research in process dynamics control and more recently in applied pharmaco-kinetics. He has authored over 40 technical papers and one audio short course.

TABLE 1
Course Outline—Staged Operations

I.	Vapor Liquid Equilibrium Review
II.	Enthalpy Concentration Diagrams
III.	One Stage Flash Calculations
IV.	Ponchon Savarit Method
V.	McCabe-Thiele Method
VI.	Design Considerations—Flooding, Weeping, Tray Efficiency
VII.	Shortcut Techniques
VIII.	Multicomponent Column Calculations
IX.	Energy Conservation

There are two other benefits to including the energy conservation material. First, evaluating energy conservation measures forces one to focus on economics. Thus, the staged operations course reinforced the students' experience in their process design and evaluation courses. Secondly, energy conservation generally involves good, sound engineering. Invariably it only takes an undergraduate training to appreciate the conservation techniques. What students learn is that energy conservation measures already exist and the question of their use depends primarily on economics.

The purpose of this paper is to discuss how energy conservation can be integrated into a course on staged operations. Table 1 gives an outline of the material covered in the course. Topics I to V were taught in the usual way without consideration of energy conservation. Some energy conservation material was introduced in covering topics VI and VII. For the somewhat dry subject matter such as flooding, tray

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efficiencies, etc., the energy conservation implications of these topics helped greatly to motivate students. During the three week period when the students worked on a multicomponent computer project, lectures on energy conservation were given.

SOURCES OF ENERGY CONSERVATION MATERIAL

Essentially all of the energy conservation material that is required can be gotten from the literature. The two primary sources that were used are the Department of Energy (DOE) Technology Transfer Manual [10] and Shinskey's text on distillation control [11]. The DOE manual lists over 50 journal references. The Mix [9] article cited earlier is also useful and it presents a number of rules of thumb.

In the DOE manual and Mix article energy information is given on the 29 most important towers in the petroleum industry as well as for the 131 key towers in the chemical industry. This information includes the energy required/lb product, the number of trays, reboiler temperature and condenser temperature. The DOE manual divides energy conservation measures up into three broad categories: as shown in Table II.

TABLE II

Energy Conservation Measures In Distillation

A. CHANGES IN OPERATING PROCEDURE
    1. Lower reflux operation
    2. Lower pressure operation
    3. Changing feed plate location
    4. Proper maintenance
    5. Reducing heat exchanger fouling
B. MODERATE INVESTMENT MEASURES (up to $50,000)
    1. Insulation particularly for valves and flanges
    2. Waste heat recovery
    3. Retraying for higher efficiency/lower pressure drop
C. MAJOR INVESTMENT MEASURES (over $50,000)
    1. Advanced instrumentation and control
    2. Heat pumping
    3. Intermediate condensers and reboilers
    4. Two stage condensation
    5. Multiple tower operation

At this point it is useful to discuss three typical examples that were used in the course. Other examples are given in the DOE manual and homework problems can be developed from them.

Example 1: Lower pressure operation.

Fig. 1, taken from Shinskey's text [11], shows a typical operating window for a butane splitter with the various column constraints labeled. It is necessary for a column to operate within these constraints, or window as they are sometimes called. The dashed curves, labeled contours of constant separation, are for a fixed feed (F) and a fixed product split (x_D, x_B). It is possible to use Fig. 1 to show that minimum energy consumption corresponds to minimum pressure operation. Since coolant temperature sets column pressure, when favorable cooling conditions arise one should take advantage of them and minimize column pressure. This minimum pressure can be determined from the intersection of the condenser constraint and the appropriate contour of constant separation.

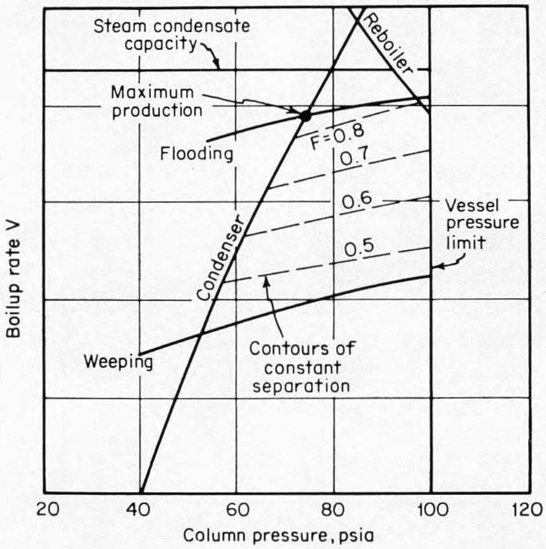

FIGURE 1. Typical operating windows for a butane splitter, illustrating that production may be maximized at the condenser constraint. (From "Distillation Control," by F. G. Shinskey, © 1977. Used with permission of McGraw-Hill Book Company.)

The calculation of the constraints and the contours of constant separation is straightforward and an excellent homework assignment. For example, the flooding curve is a simple rearrangement of the standard flooding correlation given by Van Winkle [14]

$$V = A\left(\frac{\sigma}{20}\right)^{0.2}\sqrt{\rho_V(\rho_L-\rho_V)}\; f\left(\frac{L}{V}\sqrt{\frac{\rho_V}{\rho_L}}\right) \tag{1}$$

Similarly the weeping constraint can be calculated from standard correlations. The reboiler and condenser constraints are heat transfer constraints. For the condenser assume a constant coolant temperature, T_C, constant heat transfer coefficient, U, and fixed area, A. Changes in column pressure will change the temperature of the overhead product. For nearly pure products this temperature pressure relationship is given by the Clausius Clapeyron equation

$$P = P_o \exp\left[\frac{\Delta H}{R}\left(\frac{1}{T_o}-\frac{1}{T}\right)\right] \tag{2}$$

As P increases the temperature at the top of the tower increases and the amount of heat that can be transferred increases. If this heat is assumed to be only latent heat then V and P can be related along the condenser constraint as

As can be seen, lower pressure operation gives substantial energy savings. Such savings can occur at night, during the winter and during a rain storm for air cooled condensers.

$$V = \frac{UA}{\lambda}\left[\frac{1}{\frac{1}{T_o}-\frac{R}{\Delta H}\ln\frac{P}{P_o}} - T_C\right]_{\ln\text{ mean}} \tag{3}$$

The reboiler constraint can be similarly calculated. The steam condensate capacity constraint and the vessel pressure constraint are self explanatory.

The contours of constant separation can be calculated using any of several shortcut techniques. The equation of Jafarey et al. [5] will be used.

$$N = \frac{\ln\left(\frac{x_D}{1-x_D}\cdot\frac{1-x_W}{x_W}\right)}{\ln\left[\frac{\alpha}{\left(1+\frac{1}{Rx_F}\right)^{1/2}}\right]} \tag{4}$$

For a fixed column separating a fixed feed into fixed products, Eq. (4) shows that the relative volatility, α, and the reflux ratio, R, are related as

$$\frac{\alpha}{\sqrt{1+\frac{1}{Rx_F}}} = \text{Constant} \tag{5}$$

The reflux ratio and the vapor boilup are related as

$$V = (R+1)\,F\left[\frac{x_F-x_B}{x_D-x_B}\right] \tag{6}$$

Assuming that the reboiler and condenser heat loads are equal and that only latent heat effects are important, the energy to run the tower is given as

$$Q = \lambda V \tag{7}$$

As tower pressure is lowered due to the availability of lower cooling conditions, several effects occur. Tray efficiency decreases and α and λ increase. Table III shows the results of using Eqs. (5)-(7) on Shinskey's butane splitter. The constant in Eq. (5) was calculated from Shinskey's values for a 120°F condensate temperature. The effects of tray efficiency are not included in Table III. As can be seen, lower pressure operation gives substantial energy savings. Such savings can occur at night, during the winter and during a rain storm for air cooled condensers. All of these cases result in a lower T_C in Eq. (3) and the condenser constraint is shifted to the left.

One of the interesting aspects of the calculations given in Table III is that relatively small increases in α are translated into relatively large decreases in energy consumption. Kister and Doig [6] [7] have published papers on the effect of pressure on column performance and these papers are useful supplements to Shinskey's text.

TABLE III
Energy Required to Separate Butanes at Constant Feed Conditions

(x_F = 0.5; 97-3 Split)

Cond. Temp °F	Tower P (psia)	α	λ (BTU/lb)	V/F	Q/F	Air Temp °F
120	95.2	1.32	129	5.00	645	76
100	71.9	1.35	135	4.09	552	61
80	53.1	1.38	140	3.48	487	45
60	38.1	1.41	145	3.03	439	28

Another important aspect of Fig. 1 is that it can be used to discuss the concept of maximizing throughput. For the butane splitter maximum throughput occurs at the intersection of the condenser and flooding constraints. For other systems maximum throughput can occur at the intersection of the reboiler and flooding constraints [11], [6], [7]. The slope of the flooding curve relative to the slope of the contours of constant separation determines the maximum throughput point. In going through either the minimum pressure analysis or maximum throughput analysis students see the importance of such mundane considerations as flooding.

Example 2: Retraying for higher efficiency.

In the DOE manual retrofitting old towers with more efficient trays is discussed. The example chosen for illustration is a naphtha debutanizer shown in Fig. 2. In calculating energy conservation results, the Eduljee [2] fit of Gilliland's [4] correlation is used

$$\frac{N - N_{min}}{N + 1} = 0.75 \left[1 - \left(\frac{R - R_{min}}{R + 1} \right)^{0.5668} \right] \tag{8}$$

The Underwood equation [12] [13] can be used to calculate R_m and N_m can be calculated from Fenske's equation [3]. By increasing tray efficiency, the number of theoretical plates N is increased and the reflux ratio R can be decreased.

To estimate energy savings assume that ΔN is the increase in N and that this produces a ΔL reduction in reflux. From Eq. (8) and the column material balance ΔL can be calculated. The resulting energy savings are approximately

$$\Delta Q = \Delta L \, \lambda \tag{9}$$

The results presented in the DOE manual are given in Table IV. The cost of new trays was estimated to be $11,300 and the installation charges were estimated to be between 50% and 100% of tray costs.

TABLE IV

Retrofitting Trays for Naphtha Debutanizer

	Case 1	Case 2	Case 3
Increase Theoretical Trays by	2%	5%	10%
R (Gilliland)	2.12	2.04	1.94
Energy Savings, (10^6 BTU/hr)	0.12	0.32	0.59
Annual Savings @ $2.50/$10^6$ BTU	$2376	$6369	$11,682
Payout time (yrs) for $16,950	7.1	2.7	1.5
Payout time (yrs) for $22,600	9.5	3.5	1.9

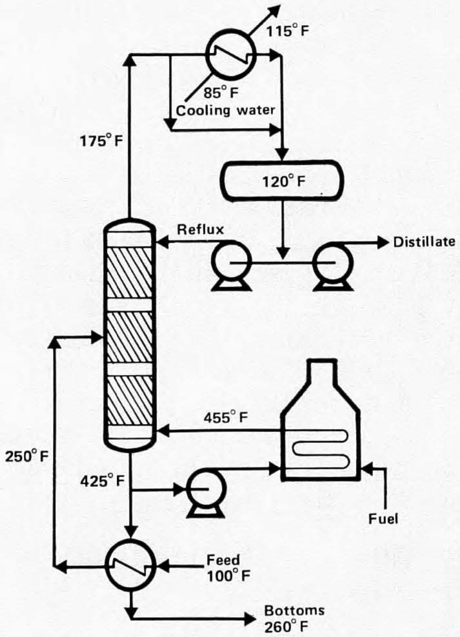

FIGURE 2. Naphtha Debutanizer [**Taken from DOE Manual (1980)**].

The DOE manual estimates that a 3% increase in N is necessary to achieve a maximum reasonable payout time of 5 years. However, this estimate is based upon relatively cheap energy ($2.50/$10^6$ BTU) and therefore it should drop with increasing energy costs.

Example 3: Heat pumped towers.

In the DOE manual a propane/propylene splitter was chosen to illustrate heat pump economics. This system involves reboiler flashing, shown in Fig. 3. With reboiler flashing the bottoms product is used as the working fluid in the refrigeration loop. The economics for heat pumping the propane/propylene splitter are given in Table V. As can be seen, substantial energy and dollar savings can be realized by going to a heat pump design in this case.

The DOE manual gives calculation procedures for determining energy and dollar savings for all the examples discussed. Using these procedures the results in Table V can be calculated. In addition the manual gives detailed guidelines for application of each of the energy conservation measures. The most important guideline for heat pumping is that the ΔT between the condenser and reboiler should be less than 65°F. An interesting homework problem can be given to illustrate this guideline. Suppose that two engineers decide to spend the same amount of money to reboil a tower. One buys low pressure steam at \$2.50/10^6 BTU and uses this steam directly in the reboiler. The other buys high pressure steam at \$3.50/10^6 BTU, and uses this steam to run a compressor in a heat pump arrangement. If the condenser temperature is 120°F at what ΔT between the reboiler and condenser will the heat pumped tower begin to be competitive with an ordinary tower? Assume reasonable efficiencies and neglect the added equipment costs for the heat pumped system. For 80% efficient compressor and a 33% efficiency for generating work from steam the answer can be calculated from the Carnot cycle equation as

$$\Delta T = (\$2.5/\$3.5)(0.33)(0.8)(580°R) \quad (10)$$
$$= 109°F$$

The difference between 109°F and the DOE recommendation of 65°F results from the added capital and maintenance costs for the heat pumped system.

SUMMARY

The three examples which have been presented are typical of those which can be incorporated into a standard staged operations course. More than enough material is available from literature sources to easily cover the subject of energy conservation. Because of the topical nature of the material student interest and motivation are high. Energy conservation involves good, sound engineering and it forces students to consider the economic aspects of their designs. Lastly, students begin to learn about column operation. For all these reasons it is felt that energy conservation is a useful addition to any course, but in particular to one on staged operations. □

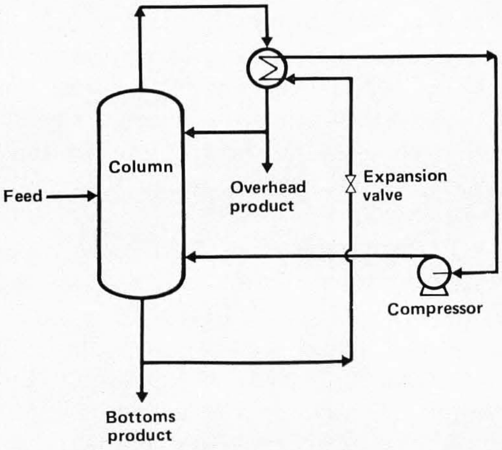

FIGURE 3. Reboiler Flashing [Taken from DOE Manual (1980)].

TABLE V
Economics for the Application of a Heat Pump to a Propane/Propylene Splitter*

Operating and economic factors	Conventional tower design	Reboiler flashing as a retrofit	Reboiler flashing on a new column
Column pressure, psia	275	275	275
Overhead temperature, °F	115	115	115
Bottoms temperature, °F	135	135	135
Steam consumption, 10^6 BTU/hr	101†	12‡	12‡
Cooling water, 10^6 BTU/hr	101	6	6
Utility costs, 10^6 \$/yr	3.06	1.10	1.10
Increased maintenance, 10^6 \$/yr		0.28	0.28
Savings, 10^6 \$/yr		1.68	1.68
Additional capital cost, 10^6 \$/yr		3.44	2.04
Simple payout, yrs		2.1	1.2
After-tax ROI, %		24.4	41.2

*All costs are in 1978 dollars.
†Low-pressure steam (valued at \$2.50/10^3 lb).
‡High-pressure steam (valued at \$3.50/10^3 lb).

Nomenclature

A = Area
C_p = Heat capacity
f = Function
F = Feed flow
H = Enthalpy
L = Reflux flow
N = Theoretical number of trays
P = Pressure
Q = Heat duty
R = Reflux ratio
T = Temperature
U = Heat transfer coefficient
V = Vapor flow
x = Mole fraction

Greek Letters

α = Relative volatility
Δ = Difference
ρ = Density
λ = Latent heat of vaporization
σ = Surface tension

Subscripts

C = Coolant
D = Distillate
F = Feed
L = Liquid
min = Minimum
o = Base case
V = Vapor
W = Bottoms

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ChE book reviews

TRANSPORT PHENOMENA IN LIQUID EXTRACTION

By G. S. Laddha and T. E. Degaleesan
McGraw-Hill, 1978, 485 pages

Reviewed by N. L. Ricker
University of Washington

From the title, one might expect this book to be confined to the study of theoretical and experimental developments in the field of transport phenomena. While this is the authors' main emphasis, they also give an overview of other important facets of the practice of liquid extraction. The general orientation is very similar to the well known book by Treybal (1963)*, and it seems appropriate to use Treybal's work as a frame of reference for this review.

Laddha and Degaleesan begin with a brief discussion of common industrial applications of liquid extraction, followed by chapters devoted to the fundamentals: phase-equilibrium thermodynamics, theories of diffusion and interphase mass transport, and calculational methods for stagewise extraction and countercurrent differential extraction. The material follows a logical sequence, and practicing engineers will be comfortable with the format, which emphasizes conventional graphical methods, overall NTU's and HTU's, etc. Treybal, however, covers much of the same material in more depth. Also, Laddha and Degaleesan fail to cite the more recent theories for the prediction of liquid-liquid equilibria, and they do not discuss the use of modern calculational methods for extractor design and simulation. There is an incorrect statement, repeated in several places, that the distribution coefficient is given by *slope* of the distribution curve, which is not true in general.

The next two chapters deal with the behavior of single drops and multiple interacting drops dispersed in a continuous phase, with an emphasis on the fluid dynamics and mass transfer characteristics of such systems. There is also a qualitative discussion of the important Marangoni effects. The material is presented in a unified form, whereas in Treybal it is much more scattered.

The next major section of the book begins with a description of the different types of extraction devices used in practice and gives a brief summary of the factors that might influence the selection of a device for a specific application. Following this, six common types of contactors: spray, packed, perforated-plate, rotary-agitated, and pulse-agitated columns, and mixer-setter extractors, are treated in individual chapters. Each chapter contains performance correlations and design criteria that can be used for the given contactor. These chapters comprise about one half of the book, and are perhaps its best feature.

The final chapter reviews the special problems that arise when extraction is accompanied by

Continued on page 96.

**Liquid Extraction*, by R. E. Treybal, McGraw-Hill, 1963.