

# DESIGN OF SEPARATION UNITS USING SPREADSHEETS

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Most design calculations in an undergraduate separations course involve solving a combination of mass balance, mass transfer, and equilibrium equations. The resulting system of equations is usually not solved analytically for two reasons: 1) the system of equations is almost always nonlinear, and 2) some of the information (typically the equilibrium data) is not available in analytical form. Before the advent of digital computers, the only option available to teachers and students alike was to use graphical solution strategies. In recent years, however, the speed of computers has increased to such an extent that even lower-end personal computers have sufficient power to solve these design equations.

In choosing an application to solve the system of equations, one must decide between faster, task-specific “separations” programs (bought commercially, written in-house, or a combination of the two)<sup>[1]</sup> and more general “equation solving” programs (e.g., Mathematica, Maple, HiQ, etc.).<sup>[2]</sup> The task-specific programs have the advantage that both the

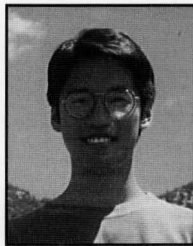
input (the problems you choose) and the output (how the results are displayed) can be rather complex. The disadvantage is that the equations and the solution strategy are completely transparent to the user. Equation-solving programs alleviate this problem but require that students learn what may be rather complex programs. Although each strategy has its advantages, we have chosen to use a simple equation-solving application to teach separation-unit design.

Although many programs can be used to solve systems of equations, we have chosen simple spreadsheet programs<sup>[3]</sup> that can perform complicated mathematical calculations<sup>[4,5]</sup> and display the solutions in a variety of tabular and/or graphical forms. The matrix-like structure of the spreadsheet is ideal for solving a system of coupled linear algebraic equations using Gauss-Jordan Elimination<sup>[6]</sup> or simple matrix inversion. Other techniques can be used to solve more complicated nonlinear equations on spreadsheets, including systems of both ordinary and partial differential equations.<sup>[7]</sup> The limited power and speed of most spreadsheet applications is more than compensated for by the ease of “programming” and the immediate presentation of results.

## AN EXAMPLE: DISTILLATION

McCabe-Thiele and Ponchon-Savarit diagrams are the most common graphical solution strategies taught in a separations course. Realizing that this distillation-column design is merely the graphical solution of a series of sequential, nonlinear equations, one can construct a McCabe-Thiele diagram using a spreadsheet. Assuming a total condenser is used, the distillate composition is equal to the vapor composition leaving the top tray. With the additional assumptions of constant relative volatility and constant molar overflow, the liquid composition leaving the top tray can be calculated using the equilibrium relationship. A mass balance on that tray then yields the vapor composition entering that tray from the tray

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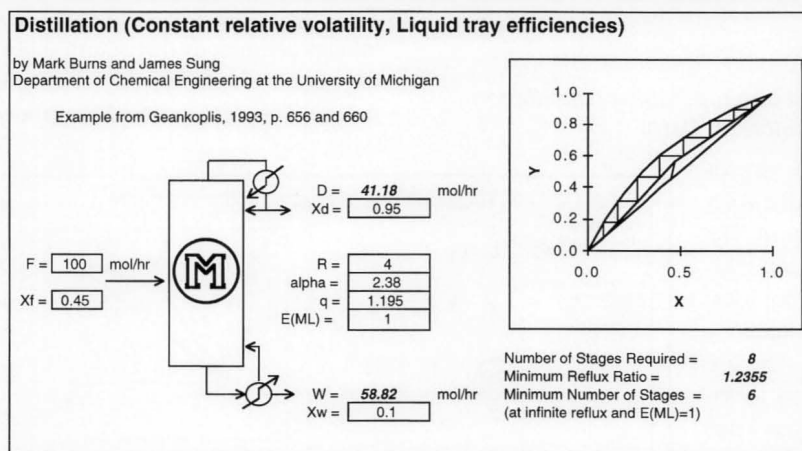
below. Using the equilibrium relationship again, the liquid composition can be calculated on the next tray and so on. Each of these equations is entered into a particular cell on the spreadsheet, and the resulting tray compositions can be plotted on an x-y diagram.

Figure 1 shows the parameter entry and graphical results section of such a spreadsheet. Note that although we have chosen Microsoft Excel

(version 4.0) for all the examples in this paper, one should be able to incorporate the concepts shown into almost any spreadsheet program.

The parameters, including the reflux ratio ( $R$ ), the relative volatility ( $\alpha$ ), the feed composition ( $X_f$ ), flow rate ( $F$ ), and quality ( $q$ ), the distillate ( $X_d$ ) and bottoms ( $X_w$ ) compositions, and the tray efficiency ( $E(ML)$ ), are entered into the boxes next to the appropriate symbols. The spreadsheet program then calculates (within seconds) the number of trays required for the separation and plots a McCabe-Thiele diagram. Changing the value in any of the boxes and pressing "Enter" immediately updates the screen with the new design. Note that no macros (prerecorded series of commands or manipulations) are required to perform any of these design calculations.

There are many advantages to using spreadsheets such as this one in a separations course. The most obvious advantage is that, from a teaching point of view, the instructor can spend a significant amount of time discussing the phenomena of distillation as opposed to the technique of graphical calculation. With a notebook computer, an LCD display, and an overhead projector, the instructor can use the spreadsheet during class to show the effect of different variables on the separation design. For example, one can slowly decrease the reflux ratio until a pinch-point occurs to visually calculate the minimum reflux ratio, or increase the reflux ratio to show that the operating lines collapse to the  $y=x$  line. By gradually changing one variable at a time, 50 to 100 column



**Figure 1.** Parameter entry section of a distillation spreadsheet. After entering the design parameters (boxes), the spreadsheet calculates the distillate ( $D$ ) and bottoms ( $W$ ) flow rates, the number of stages required, the minimum reflux ratio, and the minimum number of stages. After a new parameter is entered, the calculated values are immediately updated.

designs can be done in a fifty-minute lecture! If these designs are saved to disk, students can then take these same spreadsheets home and use them to solve calculation-intensive homework problems.

The disadvantage of this technique is that, if one avoids the use of macros, some structures that are relatively easy to accomplish in a computer program must be given careful thought in a spreadsheet. For example, a

series of nested "IF" statements must be used in the mass balance section of the distillation spreadsheet to insure that the proper "operating line" is used (upper or lower). Also, since the solution is recorded in a specific location on the spreadsheet, there are restrictions as to the maximum number of stages that can be calculated. In the spreadsheet shown in Figure 1, the equations were copied into 20 rows corresponding to 20 trays, resulting in a 20-tray maximum for that particular spreadsheet. We have found this limit sufficient for instructional purposes, although there is no reason why a spreadsheet with a limit of 100 or more stages cannot be constructed.

There are many possible problems that the students can solve with this spreadsheet or slight modifications of it. Retrofits can be performed by varying the parameter of interest until the spreadsheet returns the stage number of the existing column. Multiple feeds, sidestreams, and mislocated feeds can easily be handled by changing the "IF" statements that control the choice of operating line. More extensive modifications allow the inclusion of heat effects by adding an energy balance to the previously described equations. Also, actual tabulated data can be used in place of analytical equilibrium and enthalpy expressions.

## USEFUL MATHEMATICAL TECHNIQUES ON SPREADSHEETS

Although distillation with constant relative volatility can be solved using successive substitution, many real separa-

tion systems have complexities that make their design on spreadsheets more complicated (see Table 1). Over the last several years, we have found that a number of mathematical techniques are useful in solving a wide variety of separation problems. They are listed below with a description of their implementation on a spreadsheet and an accompanying separation unit design problem.

### Linear Interpolation and Lookup Tables (Distillation with Equilibrium Data)

The previous distillation spreadsheet assumed constant relative volatility ( $\alpha$ ) for the binary mixture. The vapor-liquid equilibrium of most binary mixtures, however, is not ideal and is instead best represented by tabulated equilibrium data. The use of tabulated data as opposed to assuming constant  $\alpha$  is irrelevant when using graphical techniques but presents a significant problem in most analytical solution strategies.

Using tabulated data in spreadsheets is quite simple due to the tabular format of the spreadsheets. Once the equilibrium data is entered, interpolation between data points (a necessary operation when calculating equilibrium values) can easily be accomplished using either cubic (or higher) spline fits or simple linear interpolation. We have found that linear interpolation is preferred in almost all cases because (a) the calculations are extremely easy, (b) an increase in accuracy in one region from a cubic spline fit is usually offset by a decrease in accuracy from an incorrect fit at another location, and (c) in a region of high curvature, extra data points can be added to increase the accuracy of the linear fit.

As an example, consider the equilibrium data entered into the spreadsheet shown in Figure 2. In "stepping down" a distillation column design, one might know the vapor composition leaving a tray and want to calculate the liquid concentration in equilibrium with that value. If the vapor composition

was, say,  $y=0.355$ , linear interpolation between the  $y=0.304$  and the  $y=0.418$  data points would yield a value of  $x=0.078$  for the liquid composition, or

$$x = x_{\text{below}} + (x_{\text{above}} - x_{\text{below}}) \frac{(y - y_{\text{below}})}{(y_{\text{above}} - y_{\text{below}})} \quad (1)$$

This interpolation is performed in the spreadsheet by using lookup commands that return the  $y$  values above and below the actual  $y$  value in the "data table" and the associated  $x$  values. The data points do not need to be evenly spaced to

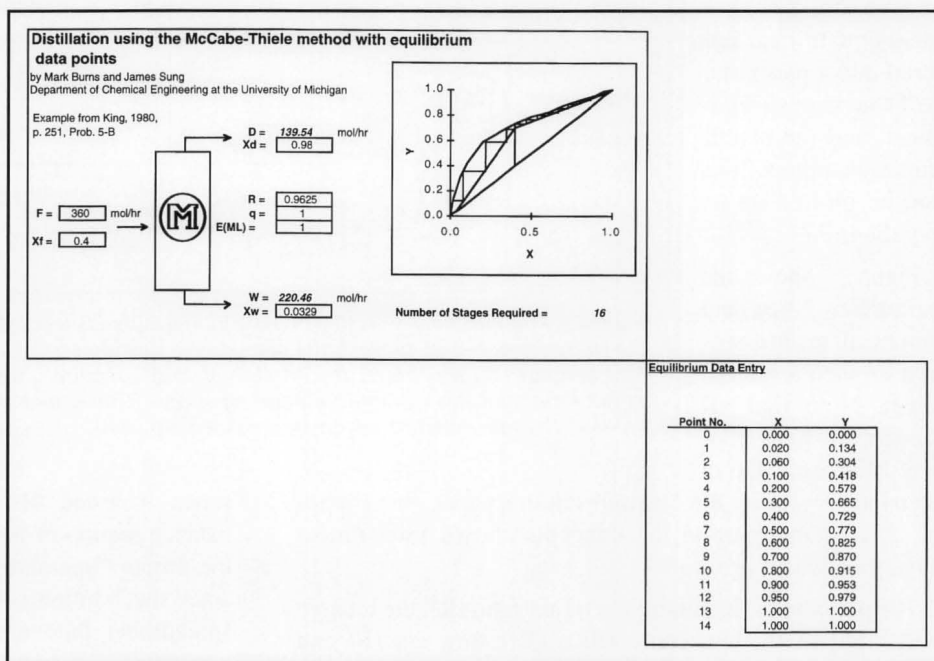


Figure 2. Distillation spreadsheet using tabulated equilibrium data. Note that the data points do not need to be evenly spaced or fill the entire table (an extra (1.0,1.0) is added at the end of the table). Although spline fits can be used to interpolate the data, we have found that using simple linear interpolation gives the most accurate results provided a sufficient number of data points is used.

TABLE 1  
 Mathematical Techniques Used in Separation Spreadsheets

Separation System	Matrix Manipulations	Jacobian/Iteration	Successive Substitution	Linear Interpolation	Quadratic Fit	Numerical Integration
<b>General Countercurrent</b>						
Unit design, linear equilibrium			✓			
Unit design, nonlinear equilibrium			✓			
Unit design, equilibrium data	✓		✓	✓	✓	
Retrofit, linear equilibrium	✓		✓	✓		
Retrofit, nonlinear equilibrium	✓	✓				
Retrofit, equilibrium data	✓	✓	✓	✓	✓	
<b>Specific Unit Design</b>						
Ideal distillation			✓			
Distillation with equilibrium data			✓	✓		
Distillation with equil./enthalpy data	✓		✓	✓	✓	
Absorption (real equilibrium data)			✓			✓
Liquid/Liquid extraction (immiscible)	✓					
Liquid/Liquid extraction (miscible)	✓		✓		✓	

perform these calculations and there is no set maximum number of points that can be used in the table.

Figure 2 also shows the earlier distillation spreadsheet modified to include equilibrium data and lookup commands. Although 13 data points are shown in the example (the 14th is a repeat), the table can be expanded to include 100 or more points. For display purposes (and for most calculations), the 14 points produce a relatively smooth curve. Note that, for low x-values where the slope of the equilibrium curve is large, additional data points have been added. Also, several columns between "x" and "y" data columns are hidden that shift the x- and y-values up one row; this technique makes interpolation with lookup commands much simpler.

### Matrix Inversion (Countercurrent Distribution)

For the design of countercurrent separation systems, successive substitution is needed because the number of stages that will be used in the system is unknown. If the design involves a known number of stages (e.g., retrofitting a separation to an existing column), then matrix techniques can be used instead. Most spreadsheets include basic matrix-manipulation commands such as matrix inversion and multiplication. Although other techniques can be used to solve the

equations, the simplicity and speed of matrix manipulations on spreadsheets makes matrix techniques particularly attractive.

As an example, one can calculate the separation that would be obtained for a countercurrent distribution system (such as immiscible liquid-liquid extraction). If the equilibrium distribution coefficient is constant (linear equilibrium relationship) and the number of stages is fixed, the mass balance equations reduce to a set of linear algebraic equations. Once the flow rates and compositions of the entering streams are specified along with the equilibrium constant ( $K=y/x$ ), the equations for a 5-stage system are

$$-(L + KV)X_1 + (KV)X_2 = LX_{in} \quad (2)$$

$$LX_1 - (L + KV)X_2 + (KV)X_3 = 0 \quad (3)$$

$$LX_2 - (L + KV)X_3 + (KV)X_4 = 0 \quad (4)$$

$$LX_3 - (L + KV)X_4 + (KV)X_{out} = 0 \quad (5)$$

$$LX_4 - (L + KV)X_{out} = -Y_{in} V \quad (6)$$

where X and L are the composition and flow rate of one liquid, and Y and V are the composition and flow rate of the other. Figure 3(a) shows the flow diagram for the process.

The equations above can also be written in matrix notation:

$$\underline{A} \underline{X} = \underline{b} \quad (7)$$

To solve for  $\underline{X}$ , the matrix  $\underline{A}$  is first inverted using the matrix inversion command. The matrix multiplication command is then used to find the product of the inverted matrix and the vector  $\underline{b}$  or

$$\underline{X} = \underline{A}^{-1} \underline{b} \quad (8)$$

The composition of the other stream ( $\underline{Y}$ ) is found by merely multiplying  $\underline{X}$  by the equilibrium constant, or

$$\underline{Y} = K \underline{X} \quad (9)$$

The section of the spreadsheet that performs these calculations is shown in Figure 3(b). The coefficients of the above equations are entered into the matrix  $\underline{A}$ . Calculations are performed each time a new flow rate, equilibrium constant, or composition is entered into the spreadsheet. For nonlinear equilibrium relationships, a similar spreadsheet can be constructed except that an iterative scheme is necessary (Newton's method, multivariable:

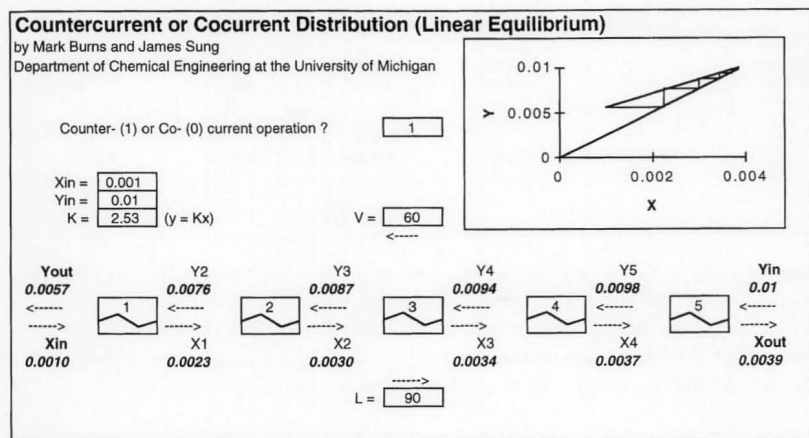
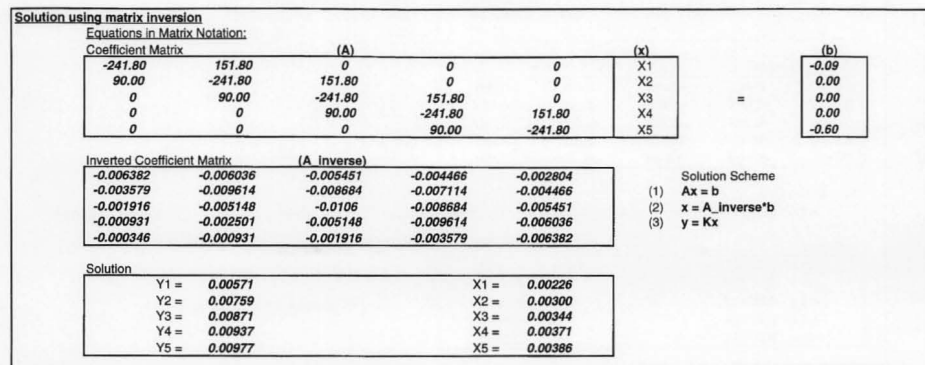


Figure 3 (a) (above) Data entry section for staged countercurrent or cocurrent separation assuming linear equilibrium and immiscible phases (liquid-liquid extraction, absorption, adsorption, etc.).

(b) (below) Matrix calculation section of spreadsheet.



see Figure 4). The nonlinear component-mass-balance equations for each stage are entered into the matrix  $\underline{f}$ . The derivative of each equation with respect to each variable is then entered into the Jacobian matrix and used to direct the iteration steps. The equation

$$\underline{x}_{k+1} = \underline{x}_k - \underline{J}^{-1} \underline{f}_k \quad (10)$$

describes this process where  $k$  is the iteration step and  $\underline{J}$  is the Jacobian matrix. This iterative spreadsheet usually converges within seconds.

### Numerical Integration (Absorption)

For staged separation systems, such as distillation in tray columns, stage-by-stage calculations need to be performed, as shown earlier. Separations in packed columns, however, require integration of the mass-transfer driving force before an accurate design can be made. This integration is one of the easiest calculations to perform on a spreadsheet and is used to calculate the necessary column length provided the driving force is known as a function of position or composition.

Packed column absorption is a typical separation system in which the driving force can be calculated as a function of composition. Although many different forms of the design equations exist, we use the following form of the absorption equations:<sup>[8]</sup>

$$L_C = \frac{G_S}{K_Y a} \int_{y_{out}}^{y_{in}} \frac{(1-y)_{*m}}{(1-y)^2 (y-y^*)} dy \quad (11)$$

where  $L_C$  is the length of the column,  $G_S$  is the solute-free gas flow rate,  $k_y$  is the overall mass transfer coefficient,  $a$  is the surface area available to mass transfer per column volume,  $y_{in}$  and  $y_{out}$  are the inlet and outlet gas concentrations,  $y^*$  is the equilibrium gas concentration based on the liquid-phase concentration, and  $(1-y)_{*m}$  is defined as

$$(1-y)_{*m} = \frac{(1-y^*) - (1-y)}{\ln \left[ \frac{1-y^*}{1-y} \right]} \quad (12)$$

In Eq. (11), the term  $(y-y^*)$  is the driving force for mass transfer. This driving force must be modified when dealing with concentration solutions to include variable flow rates  $((1-y)^2)$  and diffusion-induced convection  $(1/(1-y)_{*m})$ .

Substituting Eq. (12) into Eq. (11) and rearranging, we get

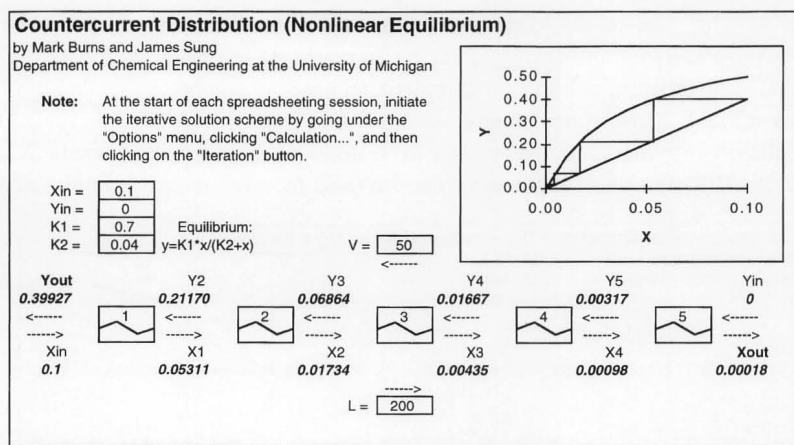
$$L_C = \frac{G_S}{K_Y a} \int_{y_{out}}^{y_{in}} \frac{1}{(1-y)^2 \ln \left[ \frac{1-y^*}{1-y} \right]} dy \quad (13)$$

This integration can be performed on a spreadsheet using the trapezoidal rule. The interval from  $y_{out}$  to  $y_{in}$  is divided into  $n$  intervals and the integral is calculated using the equation

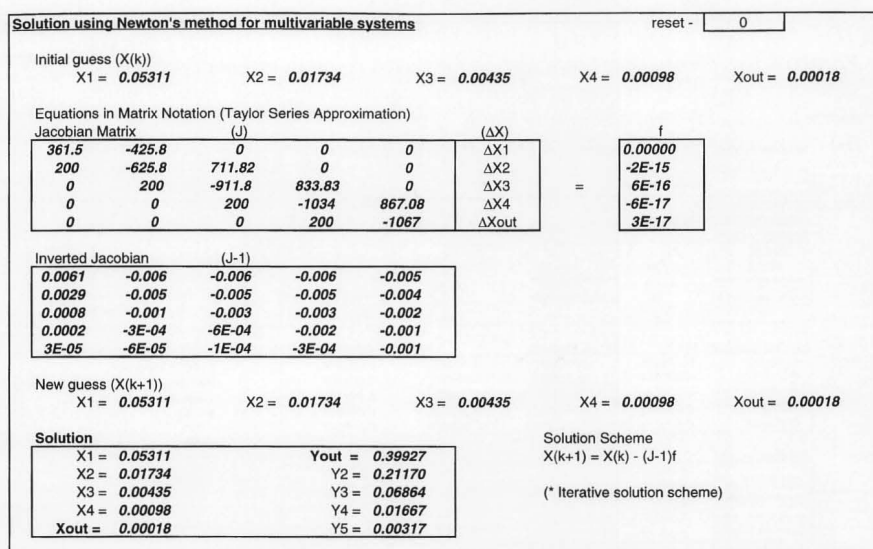
$$\text{Integral} = \sum_{i=1}^n \frac{f(y_i) + f(y_{i+1})}{2} (y_{i+1} - y_i) \quad (14)$$

where  $f(y)$  is the integrand in Eq. (13). The accuracy of this technique is a function of the number of intervals chosen ( $n$ ) with larger values of  $n$  increasing the accuracy.

A spreadsheet that performs these calculations for a continuous absorption column is shown in Figure 5. The spread-



**Figure 4. (a)** (above) Staged countercurrent or cocurrent separation assuming nonlinear equilibrium and immiscible phases (liquid-liquid extraction, absorption, adsorption, etc.). This spreadsheet is similar to that shown in Figure 3 except that a nonlinear isotherm is used. **(b)** (below) Matrix multiplication and iteration section of spreadsheet.



sheet uses tabulated equilibrium data and calculates the driving force at 20 points along the column (usually sufficient although more can be added). The trapezoidal rule is then used to calculate the integral listed above, and the length of column necessary to perform the separation in either a co- or countercurrent configuration is displayed. Note that the integral calculations in the spreadsheet are concealed inside the diagram of the column (see Figure 6). Also, in this spreadsheet, the outlet gas-phase concentration is specified; a similar spreadsheet can be developed specifying the outlet liquid concentration.

### Quadratic Fits (Liquid-Liquid Extraction)

The solutions presented thus far have involved relatively simple mathematical techniques. If these techniques were applied to liquid-liquid extraction with partially miscible phases or distillation with tabulated enthalpy data, difficulties would arise. Specifically, stagewise calculations are difficult when the stepping procedure occurs on graphs with multiple "tabulated data" lines because the endpoints of the

interpolations are not easily found. Using equations instead of data eliminates this problem but requires the user to generate and enter the equations into the spreadsheet.

An easier technique involves programming the spreadsheet to generate a least-squares quadratic polynomial to fit the data and then use the equation to design the separation system. The least-squares quadratic polynomial is defined as that polynomial,  $p(x)$ , that minimizes the sum of the squares of the error between the polynomial and the data points,  $(x_i, f_i)$ . The function to be minimized can be represented by

$$Q(f, P) = \sum_{i=1}^n [f_i - P(x_i)]^2 \quad (15)$$

where the quadratic polynomial is

$$P(x) = a_1 x^2 + a_2 x + a_3 \quad (16)$$

The coefficients  $a_1$ ,  $a_2$ , and  $a_3$  are then found by taking the derivative of  $Q$  with respect to each coefficient and setting these equations equal to zero, thus minimizing the function

$Q$ . After considerable mathematical manipulations,<sup>[9]</sup> the coefficients can be shown to be

$$\underline{a} = (\underline{X}^T \underline{X})^{-1} \underline{X}^T \underline{f} \quad (17)$$

where

$$\underline{a} = \begin{bmatrix} a_3 \\ a_2 \\ a_1 \end{bmatrix}$$

$$\underline{X} = \begin{bmatrix} 1 & x_1 & x_1^2 \\ 1 & x_2 & x_2^2 \\ \vdots & \vdots & \vdots \\ 1 & x_n & x_n^2 \end{bmatrix}$$

$$\underline{f} = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix}$$

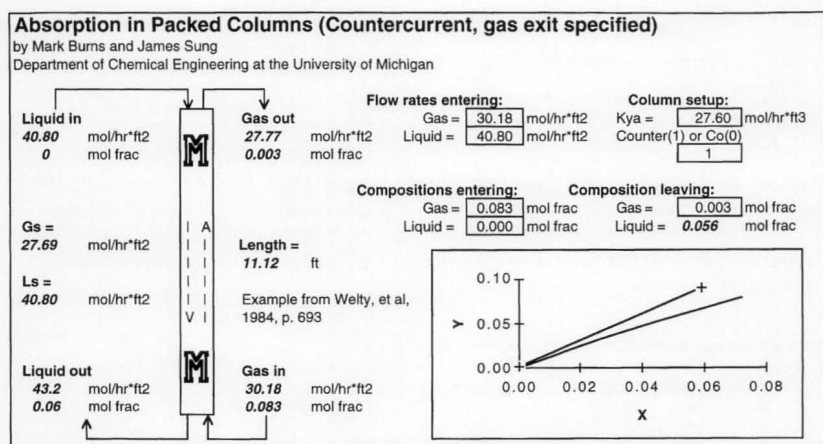


Figure 5. Continuous packed column absorption spreadsheet. After entering the parameters, the spreadsheet calculates (using Eq. 13) the length of packed column necessary to perform the desired separation. Note that, although we have specified the exiting gas composition, a similar spreadsheet can be developed that uses a specified exiting liquid composition.

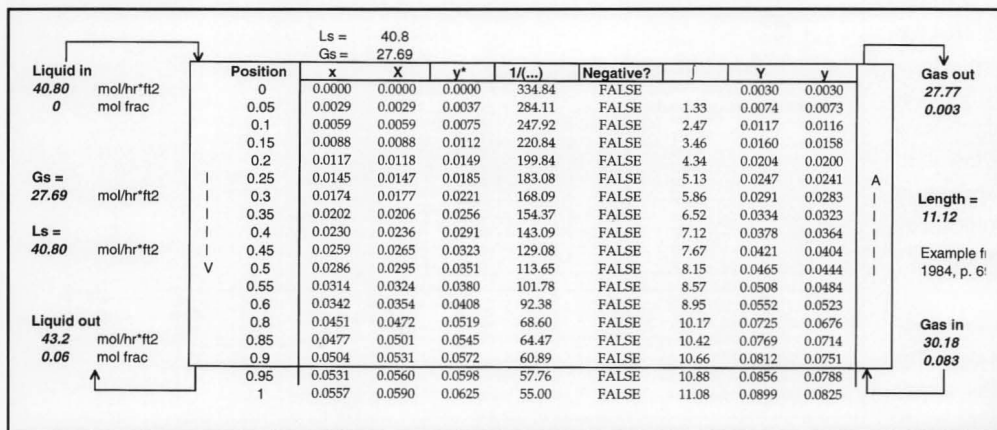


Figure 6. View of the hidden columns in the absorption spreadsheet shown in Figure 5.

Thus, the coefficients ( $\underline{a}$ ) are found from the data ( $\underline{f}$ ) using the matrix  $\underline{X}$ .

Figure 7 shows the implementation of this technique on a spreadsheet that calculates the number of stages necessary for a particular liquid-liquid extraction system. The coefficients of the calculated equation are shown in Figure 8 and can be

used throughout the spreadsheet in place of the data to calculate the required number of stages. If the fit obtained by this method is unsatisfactory, additional data points can be added to improve the fit or a higher order curve can be used. In our work, we have found that quadratic fits do remarkably well for both liquid-liquid extraction and enthalpy data in distillation.

## CONCLUSIONS

What spreadsheets lack in power, they make up for in ease of use. For a student, the results of changes to design variables in separation spreadsheets can be seen in a few seconds in tabular or graphical form. In addition to changing design variables, the student can also change the structure of the spreadsheet to design more complicated separation units. For instance, in binary distillation, multiple feeds, one or more sidestreams, or mislocated feeds can all be added to the basic spreadsheet. The techniques used to solve systems of equations in these spreadsheets can also be applied to other problems in other courses.

For an instructor, separation spreadsheets enable the lecturer to focus on the principles behind the separation processes instead of the tedious solution procedures. But care must be taken to ensure that the students do not use the spreadsheets to solve homework problems that, with the aid of the spreadsheets, are merely "plug-and-chug." During the separations course at Michigan, each spreadsheet is typically introduced in lecture when that separation unit is first discussed. Homework problems then include both simple, plug-and-chug type problems that require a single use of the spreadsheet and more complicated, multiuse problems (e.g., plot the number of trays needed to perform this distillation as a function of reflux ratio).

Qualitative homework questions are also common. More difficult problems that require the student to redesign the spreadsheet are sometimes used, but are typically reserved for group projects. Overall, the students have had a very favorable reaction to the introduction of these spreadsheets in the separation course. As a final note, all the spreadsheets shown here are available from the authors.<sup>[3]</sup>

## ACKNOWLEDGMENTS

Many students were involved in developing the spreadsheets shown in this paper. James worked on the original versions of the countercurrent distribution and distillation

spreadsheets as well as perfecting a number of the others. Wilbur Woo investigated the use of cubic splines (which we found were not necessary) and constructed the original "data" spreadsheets. Mike Johns followed Professor Frey's paper and did some simple chromatography solutions. Mike Vyvoda spent considerable time debugging the final versions and writing the all-important nomenclature tables. In addition to these students, many other undergraduates at the University of Michigan contributed to the spreadsheets through feedback in our separations course.

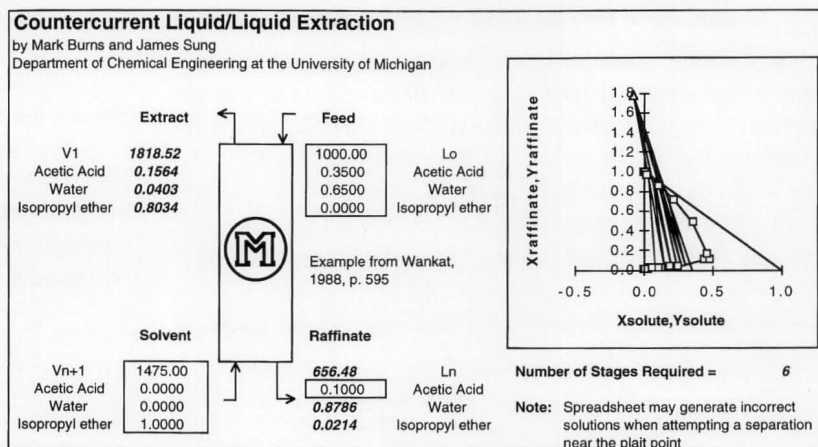


Figure 7. Parameter entry and graphical output section of the liquid/liquid extraction spreadsheet. This spreadsheet is particularly complex because "stepping" between the equilibrium curves with linear interpolation is difficult. But using a quadratic fit to the data allows easy calculation of the required number of stages for any given system.

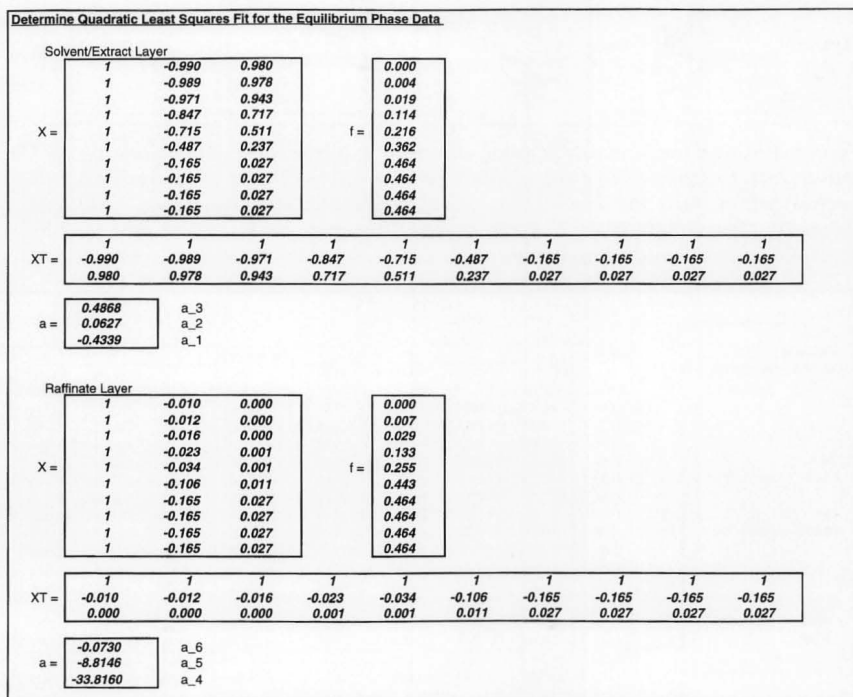


Figure 8. Calculation of the quadratic equations used in the Figure 7 spreadsheet.

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## ChE book review

### **CHEMICAL THERMODYNAMICS: BASIC THEORY AND METHODS**, 5th ed.

by Irving M. Klotz, Robert M. Rosenberg

Published by John Wiley and Sons, Inc., NY; 533 pages, \$54.95 (hard cover) (1994)

#### Reviewed by

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The fifth edition of Klotz and Rosenberg's *Chemical Thermodynamics* is similar in spirit to its four predecessors. It is a text on classical thermodynamics and its applications to mixtures, chemical reactions, and other situations of interest to chemists. It can be used both for undergraduate and graduate instruction and requires no previous knowledge of thermodynamics. The simple mathematical tools needed to understand the material are explained in the book.

The twenty-three chapters cover a wide range of topics. Following two introductory chapters on the history and objectives of classical thermodynamics and on mathematical prolegomena, the First Law and its applications to chemical reactions and to the behavior of gases is discussed. Three chapters are also devoted to the Second Law, its consequences (reversibility, spontaneity, free energy functions) and its application to simple cases of phase equilibria (e.g. the Clapeyron equation, temperature dependence of enthalpies of transition).

Other chapters discuss the Third Law, reaction equilibria, systems of variable composition, gas mixtures, the phase rule, ideal solutions, dilute solutions, activities in non-electrolyte solutions, the calculation of partial molar quantities from experimental data, the determination of activities of non-electrolytes, electrolyte solutions, free energy changes in solutions, gravitational fields, and the estimation of thermodynamic quantities. The fifth edition also contains a new chapter on simple analytical and numerical methods (least squares regression, numerical and graphical differentiation and integration). The above subjects are of obvious interest to chemical engineers, but important topics such as open systems and phase equilibria are not discussed with the depth needed in many engineering applications.

A useful feature of the book is the presence of several examples and problems dealing with biological systems. Specific topics include the calorimetric study of conformational transitions in proteins, free energy and useful work in biological systems, the dissociation of DNA, the solubility of proteins in aqueous solution, osmotic work in biological systems, and protein centrifugation. Several geological examples are also given, especially in the chapter on the phase rule. These biological and geological illustrations, the majority of which can also be found in the fourth edition, add significantly to the book's value and originality.

The book aims at training students in the use of thermodynamics for solving practical problems. This is accomplished very well indeed. Each chapter contains illustrative examples, as well as a good number of problems (typically between ten and twenty). More rigorous and satisfying discussions of the logical structure of thermodynamics are available (e.g., Denbigh's *Principles of Chemical Equilibrium*). In Chapter 3, for example, the authors define adiabatic systems by invoking the notion of thermal equilibrium; however, neither temperature nor equilibrium have been discussed at that point. Similarly, the definition of an ideal gas as one satisfying  $PV=RT$  and, in addition, having a temperature-independent energy is redundant. The latter condition follows from the former, but this can only be proved by invoking entropy, which the authors have not defined at that stage (Chapter 5).

On balance, however, the book's virtues outweigh its limitations. Few texts provide the student of chemical thermodynamics with a wider selection of exercises and examples to assist in the development of problem-solving skills. Because of this, Klotz and Rosenberg's book is useful not only for chemists, but also for biologists, engineers, and geologists.

The back cover of the copy of the book that I received from CEE for review, and that of a second copy subsequently sent to me by the publishers, says that this fifth edition contains new chapters on the thermodynamics of the electrochemical cell and on pH diagrams. This is not correct; the book does not include such chapters. I have been assured by the publisher that this matter will be corrected. □