Award Lecture . . .

SYNERGISM BETWEEN RESEARCH AND TEACHING IN SEPARATIONS

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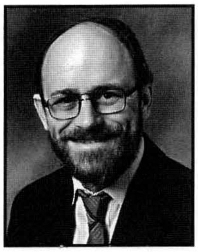

Phillip C. Wankat is Professor of Chemical Engineering at Purdue University in West Lafayette, Indiana, where he has been since 1970. He received his BSChE from Purdue and his MA and PhD degrees in Chemical Engineering from Princeton University. In 1982 he also received an MS in Education from Purdue. He was Head of Freshman Engineering at Purdue from 1987 to 1995 and its Interim Director of Continuing Engineering Education in 1996.

Professor Wankat is interested in research in separations with an emphasis on adsorption, chromatography, and distillation. He is the Editor-in-Chief for *Separation and Purification Methods* and is the author of *Large Scale Adsorption and Chromatography* (CRC Press, 1986), *Equilibrium-Staged Separations* (Prentice-Hall, 1987), and *Rate-Controlled Separations* (Chapman-Hall, 1990). He has published over 100 technical papers and ten technical book chapters. He received the ACS Award in Separation Science and Technology in 1994 and is a Fellow of AIChE and ASEE. He is the Co-Editor (with Dr. Kent Knaebel) of a new section on "Mass Transfer" in the 7th edition of *Perry's Chemical Engineers Handbook.*

Professor Wankat is interested in teaching improvement and is the co-author (with Dr. Frank Oreovicz) of *Teaching Engineering* (McGraw-Hill, 1993). He and Frank have co-taught a course for PhD students, "Educational Methods in Engineering" at Purdue since 1983. He has published over thirty articles on engineering education and is the Associate Editor of the journal *Chemical Engineering Education.* He frequently presents teaching improvement seminars and workshops. He has won several teaching and counseling awards at Purdue in addition to the Dow Outstanding Young Faculty Award, the Western Electric Award, the George Westinghouse Award, and the Chester F. Carlson Award, all from ASEE, and the Chemical Manufacturer's Catalyst Award.

I wish to thank the Chemical Engineering Division of ASEE for this award and the Union Carbide Corporation for its sponsorship of the award. It is a distinct honor to be included among the list of distinguished chemical engineers who have received the division's lectureship award.

There is considerable debate about the roles of teaching and research in the University. Astin's[1] extensive survey data shows that on a university-wide basis teaching suffers when major increases in research occur. This appears to be a resource allocation issue. For individual faculty members, the correlation between research and teaching effectiveness appears to be zero or very weakly positive.[1,2] In any case, these research results rarely get the same public attention as do the muckraking attacks by Sykes,[3] Smith,[4] and others. The voices supporting a balance of teaching and research as the ideal[5,6] tend to be more moderate and are drowned out. I feel we should continually search for a balance between teaching and research. This paper explores the synergisms between teaching and research that have made my own teaching and research richer and more effective.

In the ideal university, research and teaching are synergistic; the total output is not additive in the sense of 2 + 2 = 4, but is greater than the sum of the parts, 2 + 2 = 5, or even 6, 7, or 8. This can come about because of efficiencies in working on both teaching and research—the same effort ends up having multiple uses. And teaching and research provide deeper meaning, each for the other, in unexpected ways. Of course, there are also times when they have little in common, but this does not negate the experience of unity that results when teaching and research synergistically complement each other.

Unlike Gaul, this paper is divided into six parts: since lecturing is used to communicate for both teaching and research, it starts with lecturing; the second part is concerned with people; the next part discusses interactions in learning for both teaching and research; part 4 explores an example of interaction in a graduate-level course; examples of interactions between research and teaching in undergraduate courses appear in part 5; and part 6 asks the question, "Is synergy with service and administrative duties possible?"

PART 1

LECTURING

The most common method of teaching or reporting research results in engineering is lecturing. Any efforts a professor makes to improve lecturing skills will improve both teaching and research lectures. Three things prevent a lecture from being considered terrible:[7]

- *Not reading to the audience*
- *Speaking loudly enough*
- *Finishing on time*

Now, this is easy enough to accomplish and may help explain why only 11% of engineering students rate their instructors as average or below average.[8]

An analysis of learning in college[1] showed that student *involvement* is needed to obtain learning. This is true in all lectures. Thus, the lecturer must keep the audience engaged and generally paying attention. The positive things that can be done to improve a lecture include the following performance attributes:[2,7,8]

- *Having a positive attitude*
- *Showing enthusiasm*
- *Using visuals*
- *Making eye contact*
- *Remembering the attention span is 15 to 20 minutes*

The last point is particularly difficult in a research lecture since normally a speaker goes nonstop until the question period. But the norm is wrong. All lectures can benefit from

- *Breaks with purposeful audience activity*

The purposeful activity helps to involve the audience.

Audience analysis is also useful. Audiences hope that the speaker will

- *Keep them awake*
- *Be somewhat interesting and even funny*
- *Say something useful to them*

If the audience consists of students, they will also want to know

- *Will this material be on the test?*

Since the research lecture does not have this last motivation, it is even more important to be enthusiastic and humorous.

Note that content plays only a minor role in making a lecture interesting. Practically any content can be made interesting—or boring.

PART 2

PEOPLE

Chemical engineering is a great profession because the people involved in it have developed effective ways of solving important problems. But we often forget the importance of people. It is somewhat traditional in an award lecture to thank people who helped along the way. Without becoming excessively personal, I will briefly discuss some of the people who have influenced me.

My father was an analytical chemist who worked at UOP for forty years. One of his favorite sayings was, "What is your plan B?" I got used to looking for alternatives *before* things did not work—not bad training for a professor or a department head. Throughout high school I planned to be a chemist, but my father's advice, "Be a chemical engineer, they're treated better," was convincing. My mother's main contributions were a drive to get things done, which balanced looking for alternatives, and persistence (or stubbornness, depending on one's viewpoint) in the face of obstacles.

Professor Lowell Koppel taught the mass transfer and separations course when I was an undergraduate. He sparked my interest in distillation and separation and was the best straight (no gimmicks) lecturer I had in my education. Later, when he was my department head, he taught me that one should always challenge the premises first.

Professor Bill Schowalter was my thesis advisor at Princeton, where I did research on hydrodynamic stability analysis. This was an excellent education for research in separations since I learned how to pose problems. The greatest lesson I learned from Bill was to find out why something puzzling or unexpected occurred. One example of this involved solving the quadratic equation $ax^2 + bx + c = 0$ in the middle of a loop in a computer program. The sign of the desired solution would change while the program was running. Why? (The answer can be found at the end of this article after "Closure.") This lesson to always find out why has proven to be important in both teaching and research.

Professor Jud King's book, *Separation Processes,*[9] appeared late in 1970, just as I started to do research and teaching in separations. What a godsend it was! I learned a great deal about separations from it and used it for ten years in an elective course at Purdue. When I spent my first sabbatical at Berkeley, Jud was very supportive of my research efforts in separations at a time when I badly needed support.

On the pedagogy side, two Purdue professor of education had a significant impact on my career. Professor John

Feldhusen's course, "Educational Psychology for College Teachers," made me realize that I did not have to copy what I had seen in the classroom. Years later, Frank Oreovicz and I adapted John's course to engineering and developed a new course, "Educational Methods in Engineering." Much of John's course survives in the book *Teaching Engineering*.[2] Professor Dick Hackney let me take a course in counseling theories despite my obvious lack of preparation. He also encouraged my application to earn an MS in education, and this eventually led to my becoming Head of Freshman Engineering.

Many other people have influenced my teaching and research. They include colleagues, undergraduate students, and graduate students. Hopefully, I have had an equally positive influence on most of them.

On a personal level, in December of 1980 an amazing thing happened. I got married, calmed down, became happier, and found I was much more productive. Then we had children, and I also became responsible. So I want to thank my wife, Dot, and my children, Charles and Jennifer, for enriching my life.

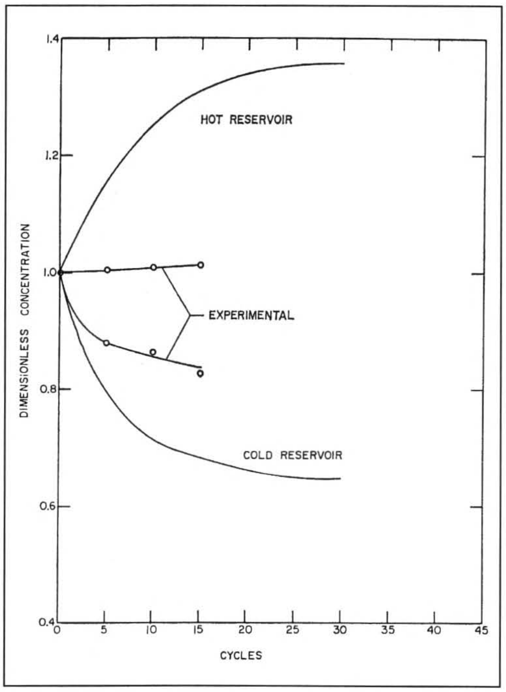

***Figure 1.** Comparison of theoretical and experimental results for discrete transfer test tube parametric pumping system. Diethyl ether stationary phase, water moving phase, acetic acid solute. Theoretical results correspond to: f_h=0.515; f_c=0.476; V_C=V_H=0; 5 stages, 2 transfers per half-cycle.*

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PART 3

LEARNING

There is no better fortune for a professor than to teach and do research in the same area. When I am learning new things about separations, it is not clear if I am doing this for research or for teaching, or for both. They build on each other. Research and teaching are a unified whole with respect to a professor's learning.

Reading Jud King's book was my introduction to the countercurrent distribution (CCD) theory of chromatography. This led to including the theory in an elective course on separations. Then I used the theory and did countercurrent distribution experiments for parametric pumping[10] and later for affinity chromatography.[11] The CCD theory has the advantages of being very simple to understand and to program on a computer. The CCD model was used extensively to model chromatography before powerful computers became inexpensive. In CCD all of the mobile phase in a stage is transferred simultaneously to the next stage. Then the mobile and stationary phases in each stage are equilibrated. After equilibration, the mobile phase is again transferred. For linear equilibrium, the fraction of the solute in the mobile phase, f, is

$$f=\frac{K'V_m/V_s}{1+K'V_m/V_s} \quad \text{where } K'(T)=C_m/C_s \tag{1}$$

Then, (1-f) must be the fraction of solute in the stationary phase. The discrete transfer step combines the stationary phase from stage i with the mobile phase from the previous stage, i-1. The mass balance is

$$M_{i,s}=f_{i-1,s-1}M_{i-1,s-1}+\left(1-f_{i,s-1}\right)M_{i,s-1} \tag{2}$$

where $M_{i,s}$ is the mass of solute in stage i after transfer step s. This model results in an equation that is essentially a finite difference form of the more complicated equations needed to describe chromatography with continuous flow. For isothermal chromatography with a pulse input, $f_{i,s}$ is a constant and an analytical solution of Eqs. (1) and (2) is easily developed.[9]

In parametric pumping the temperature and flow direction are changed periodically. A numerical solution of Eqs. (1) and (2) is easily generated.[10] The results are shown in Figure 1 for extraction parametric pumping. Although the agreement was obviously not good (probably because of evaporation of the diethyl ether), the model was useful since it did not predict the infinite separation factors that linear models for columns did. The same paper[10] included a continuous-flow model for parametric pumping. The development of that model occupied over two pages in the journal, compared to less than half a page for the discrete-transfer model. A number of other researchers subsequently used both discrete transfer and continuous-flow models to model parametric pumping and other cyclic separations.

This success with a chromatographic theory led me to take a chromatography course from Professor Buck Rogers in chemistry. Buck encouraged me to become more involved in chromatography research. I used the CCD theory to explain affinity chromatography.[11] The affinity chromatography research made it abundantly clear that biochemistry was needed, so I took two biochemistry courses, which helped further research in biochemical separations.[12] About this time I became cocky and thought I knew enough adsorption and chromatography to develop a graduate-level elective on adsorption and chromatography. Since the teacher invariably learns more than the students, I had to *really* learn the different theories of adsorption and chromatography. I spent a great amount of time studying Chapter 10 of Sherwood, Pigford, and Wilke[13] and reading the literature.

The students in this graduate separations elective voted to learn about membranes. Building on what is included in King's book, membranes were included in the course. This knowledge eventually became useful in research[14] and later became two chapters in the textbook.[15] This pattern of building on learning done for teaching to do research and then building on the knowledge gained in research to improve teaching repeats over and over again.

The knowledge of adsorption and chromatography solutions and mass transfer that I had learned while preparing to teach unexpectedly proved very useful in developing intensification procedures for adsorption,[16] elution chromatography,[17] and PSA.[16,18] The first stages of this research were done during my second sabbatical, spent at ENSIC in Nancy, France. I decided to take the time to answer a question that had nagged me for several years. In analytical liquid chromatography, the use of smaller and smaller packings had revolutionized the method and resulted in HPLC. Yet this development had no impact on adsorption operations and very little impact on large-scale chromatography, both of which have very similar mass transfer characteristics to analytical liquid chromatography. The typical answer to why small particles were not used was that pressure drop would be too large, but I was not convinced. Since I was on sabbatical, I could afford to "waste" my time to look at this question.

In one afternoon a "back-of-the-envelope" calculation convinced me that the common wisdom, based on a constrained optimization, was wrong. For example, Sherwood, Pigford, and Wilke show diminishing returns as the particle diameter decreases. But in their example, the cycle time was set constant at ten minutes. A reworking of this example[16] clearly shows that there is an advantage to reducing particle diameter if the cycle time and column length are scaled correctly.

The initial analysis was rather approximate and the next ones were a bit on the messy side. Eventually, simpler ways of solving the problem, such as the dimensionless analysis employed to analyze pressure swing adsorption (PSA),[18] were developed. This work actually used what I had learned about dimensionless analysis in my PhD thesis on hydrodynamic stability analysis, and thus it illustrates that problem-solving techniques are often transferable to very different problems. By the time this material was included in a textbook,[15] the theory had been simplified significantly. The following development is based on the textbook presentation, but can easily be extended for more complex cases. The textbook presentation takes us full circle since the results of the research are now being taught to students.

Assume that we have an adsorption column that works satisfactorily. It does not matter how this "old" design was developed. We now wish to develop a "new" design. By taking ratios of the controlling equations, we can do the new design without solving any differential equations. The pressure drop in a packed bed of rigid particles with laminar flow is

$$\Delta p = \frac{\mu v \varepsilon_e L}{K d_p^2} \tag{3}$$

where K is the bed permeability that depends only on the porosity. Taking the ratio of Eq. (3) for the old and new designs, we obtain

$$\frac{1}{R_p} = \frac{\Delta p_{old}}{\Delta p_{new}} = \left(\frac{v_{old}}{v_{new}}\right)\left(\frac{L_{old}}{L_{new}}\right)\left(\frac{d_{p,new}}{d_{p,old}}\right)^2 \tag{4}$$

The bed porosity for rigid spheres is independent of bed diameter, bed length, and particle diameter; therefore, to a first approximation K cancels out in the derivation of Eq. (4). The interstitial velocity v is related to the volumetric flow rate Q by

$$v = \frac{4Q}{\pi D^2 \varepsilon_e} \tag{5}$$

The ratio of old and new velocities is easily obtained and substituted into Eq. (4) to obtain

$$\frac{1}{R_p} = \left(\frac{Q_{old}}{Q_{new}}\right)\left(\frac{D_{new}}{D_{old}}\right)^2\left(\frac{L_{old}}{L_{new}}\right)\left(\frac{d_{p,new}}{d_{p,old}}\right)^2 \tag{6}$$

If $R_p = 1.0$, then the pressure drops in the old and new designs are equal even though the designs may look very different.

To consider the separation that is achieved, we define

$$\frac{1}{R_N} = \frac{(L/L_{MTZ})_{old}}{(L/L_{MTZ})_{new}} \tag{7}$$

where L_{MTZ} is the length of the mass transfer zone. If $R_N = 1.0$, the fractional bed use in the two designs is identical and the separation is identical. (For linear chromatography, R_N is defined as the ratio of the number of plates in the new and old designs.[17]) Substituting the expression for L_{MTZ} for a Langmuir isotherm into Eq. (7), we obtain

$$\frac{1}{R_N} = \left(\frac{Q_{new}}{Q_{old}}\right)\left(\frac{D_{old}}{D_{new}}\right)^2\left(\frac{L_{old}}{L_{new}}\right)\left(\frac{k_m a_{p,old}}{k_m a_{p,new}}\right) \tag{8}$$

This simplifies if pore diffusion controls to

$$\frac{1}{R_N} = \left(\frac{Q_{new}}{Q_{old}}\right)\left(\frac{D_{old}}{D_{new}}\right)^2\left(\frac{L_{old}}{L_{new}}\right)\left(\frac{d_{p,new}}{d_{p,old}}\right)^2 \tag{9}$$

When pore diffusion controls, Eqs. (6) and (9) relate the six variables R_p, R_N, (Q_{new}/Q_{old}), (D_{new}/D_{old}), (L_{new}/L_{old}), and $(d_{p,new}/d_{p,old})$. Four of these are selected as known and the other two are solved for. Since all of the "old" parameters are known from the old design, the new parameters are easily determined from the ratios.

If the only significance of this were scale up, the procedure would not have had much impact. The significance on economics is easily seen from a numerical example. If we set $R_p = 1$, $R_N = 1$, $(Q_{new}/Q_{old}) = 1$, and $(d_{p,new}/d_{p,old}) = 0.1$, we find that solution of Eqs. (6) and (9) gives $(L_{new}/L_{old}) = 0.01$ and $(D_{new}/D_{old}) = 1$. To keep the same boundary conditions (or the same relative amount of time processing feed), we must cycle more quickly. For the case considered here, the cycle and feed times must be scaled as

$$\frac{t_{cycle,new}}{t_{cycle,old}} = \frac{t_{feed,new}}{t_{feed,old}} = L_{new}/L_{old} \qquad (10)$$

which is a ratio of cycle times of 0.01. Thus, a very short column cycling rapidly can produce exactly the same separation with the same pressure drop for the same volumetric flow rate of feed if we reduce the particle diameter. Since the adsorbent volume is $\pi D^2 L/4$, this is a much smaller column. If the ratio $(d_{p,new}/d_{p,old})$ is a significant change, the new system will need to be redesigned to reduce dead volume.[18] Different geometries such as annular flow may become viable.[19] Now that I am finished with this research, it has caught the attention of companies that separate gases by adsorption.

PART 4

GRADUATE STUDENT PROJECTS IN COURSES

One would expect that graduate students would do a significant amount of research for their theses, and, of course, doing this research involves learning *how* to do research. By working with the students, the professor helps the students learn—which is not a bad definition of teaching. Thus, teaching and research are synergistic during normal graduate student research. Synergism can also occur between research and graduate students' projects in courses.

Several graduate-student projects in courses have eventually resulted in papers. For example, Narsi Sundaram, a student in my advanced separations course, decided he wanted to look at PSA for his course project. After a bit of searching, he decided to look at the effect of pressure drop on the repressurization and blowdown steps in PSA. I "knew" that this effect would be negligible, but since a negative result is perfectly acceptable for a project, I gave him the go-ahead. He found

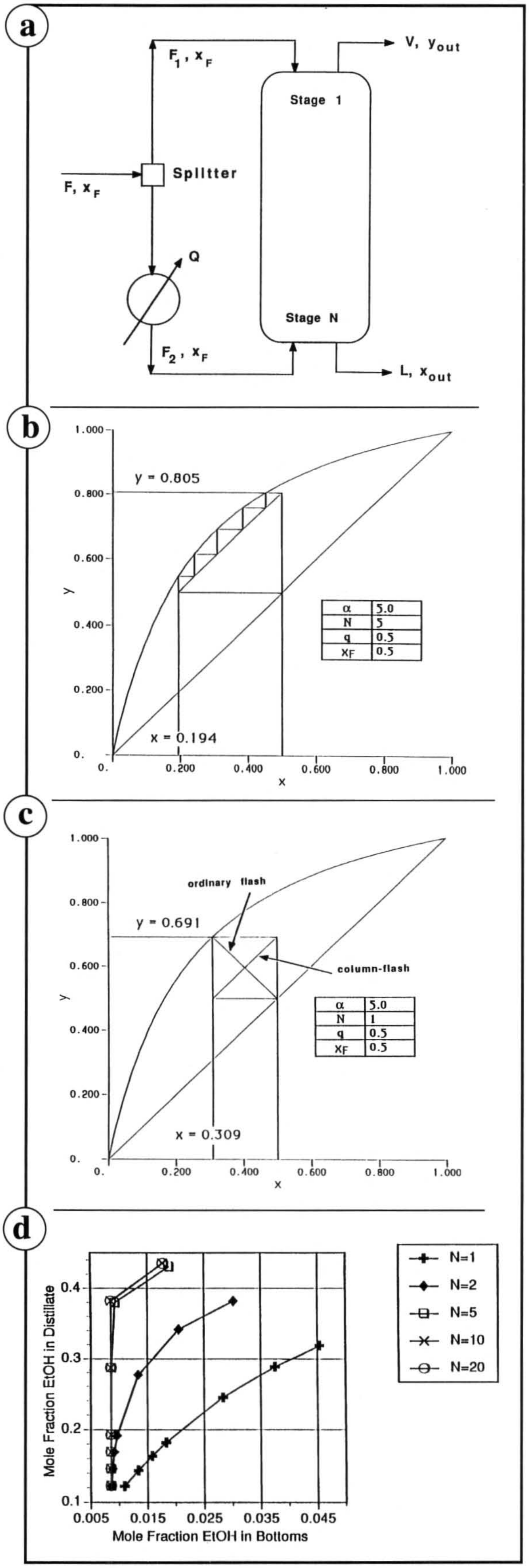

Figure 2. (a) *Two-enthalpy feed analog of ordinary flash distillation—column-flash distillation.* ***(b)*** *Column-flash distillation: N=5 equilibrium stages, q=0.5, α=5, x_F=0.5, constant molal overflow.* ***(c)*** *Column-flash and ordinary flash distillation: McCabe-Thiele analysis, N=1 equilibrium stage, q=0.5, α=5, x_F=0.5.* ***(d)*** *Effect of $q=F_1/(F_1+F_2)$ and N on separation of ethanol from water using a column-flash system. Results of Aspen Plus simulations. Equilibrium data used physical property package SYSOP18. Feed is 10 mol % water. Pressure=1 atm. From left to right in each series of seven points for a given N: LV=F_1/F_2=0.25. 0.50, 0.75, 1.00, 2.00, 3.00, 4.00.*

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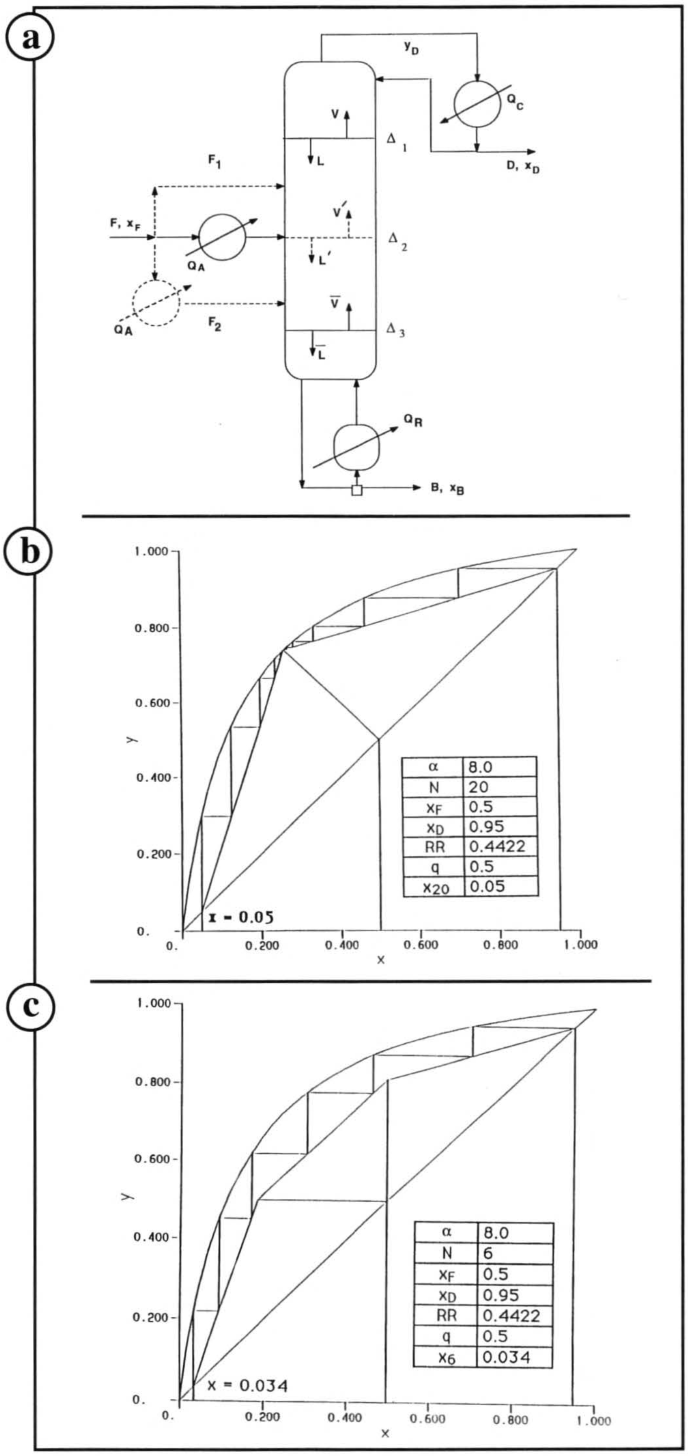

Figure 3. (a) *Ordinary complete distillation column with two-phase feed (solid feed line); complete distillation column with two-enthalpy feed (dashed lines).* ***(b)*** *McCabe-Thiele diagram for near-minimum-reflux case—ordinary column with two-phase feed: requires 20 stages to yield x_{20}=0.050.* ***(c)*** *McCabe-Thiele diagram for same reflux ratio—column with two-enthalpy feed: requires only six stages to yield x_6=0.034.*

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that under certain conditions the effect of pressure drop was much larger than anyone expected. Narsi switched his thesis topic to work with me on this in more detail, and eventually we published the result.[20] This paper led to an outpouring of other papers on the topic (unfortunately, not by me), and at least one of the major gas companies changed their computer modeling to include this effect. So, what do I know?

If space allowed, there are other examples we could explore in depth. In all cases, additional work was necessary to take the original student project and make it publishable. This type of synergism between teaching and research is relatively obvious.

PART 5

INTERACTION WITH UNDERGRADUATE COURSES

To this point, the synergisms between research and teaching have involved graduate-level courses or senior electives. There are synergisms between teaching required undergraduate courses and research, but they are fewer.

I first became interested in distillation as a junior at Purdue. I found the McCabe-Thiele diagram to be fascinating. I wanted to do research on distillation, but for many years couldn't seem to find an opening. Instead, I taught the junior-level equilibrium staged course at Purdue for many years and eventually wrote a textbook for the course.[21] Finally, during a 1992 sabbatical at the University of Florida, I started some distillation research. (Funny how these things seem to happen on sabbatical.) I had developed a new PSA process that used the feed gas for a partial purge.[22] During the hunt for other possible uses of this idea, I remembered that Suzuki[23] had shown that PSA and distillation were analogous. (Actually, Suzuki wrote that PSA can be approximately analyzed as a continuous countercurrent process.) With this (inaccurate) analogy, the column flash distillation system shown in Figure 2a[24] was developed. At first glance, it does not look like distillation since there is no reboiler and no condenser. But years of teaching that distillation is a vapor-liquid separation system with heat as the separation agent had convinced me that neither a reboiler nor a condenser is needed. Figure 2a is a form of distillation. The operating line and the McCabe-Thiele diagram are shown in Figure 2b. If there is a single stage, the result becomes the same as normal flash distillation (Figures 2c). The results of more detailed simulations done with Aspen are shown in Figure 2d. They show that column flash can achieve more separation than a normal flash.

This was interesting, but not necessarily useful. So Dave Kessler and I extended the idea to distillation columns. The eventual result was the two-feed column shown in Figure 3a.[24] A comparison of the McCabe-Thiele diagrams for the single-feed operation (Figure 3b) to the two feed-system (Figure 3c) shows that when the single-feed system would be a two-phase feed, the two-feed column is significantly better. What is meant by "better" is illustrated in Figures 4a, 4b, and 4c, which are results of Aspen simulations.

After the research was done and while Dave and I were writing the paper, I realized I had seen this type of two-feed distillation before. It is homework problem 6D15 in my distillation textbook.[21] Perhaps there was a subconscious memory that guided the research. While the paper was in the galley-proof state, Dave Manley at the University of Missouri-Rolla informed me that several variants of column flash distillation are covered by U.S. patent 4,726,826 (1988).

My next step will be to incorporate these results in the junior distillation course in the fall of '97. The column flash system will make an excellent test or homework problem. There are also enriching and stripping column examples in the paper[24] that will make novel problems for the students. My experience using Aspen for research will be helpful in using Aspen in the course.

What if you teach courses that are not in your research area? Are there still possible synergisms between teaching and research? What if you teach mass and energy balances? I admit that finding ties between a mass and energy balance course and research may be difficult. After a twenty-two year hiatus, I had the opportunity to teach the mass and energy balance course in the spring of 1997. I used the little red bible[25] as the text. The material was essentially the same as it had been twenty-two years ago, but the students had changed. Going back and reviewing the fundamentals with a different textbook did bring an increased depth to my understanding—I saw an analogy between the choice of reference states for energy balances with a heat of mixing and energy balances for adsorbers with a heat of adsorption. This understanding was helpful in current adsorption modeling research.

Another type of synergy occurred in teaching the mass and energy balance course. This was a synergy between teaching different areas. After about a fourth of the semester, I knew the course was not going well—many students were not learning. Leaning heavily on what I had written[2] and taught about how to teach, I asked the students to write down what they thought would help them learn on a 3x5 card. Using these comments as a guide, I reorganized the remainder of the course. The course improved and the end-of-semester student evaluations were quite positive.

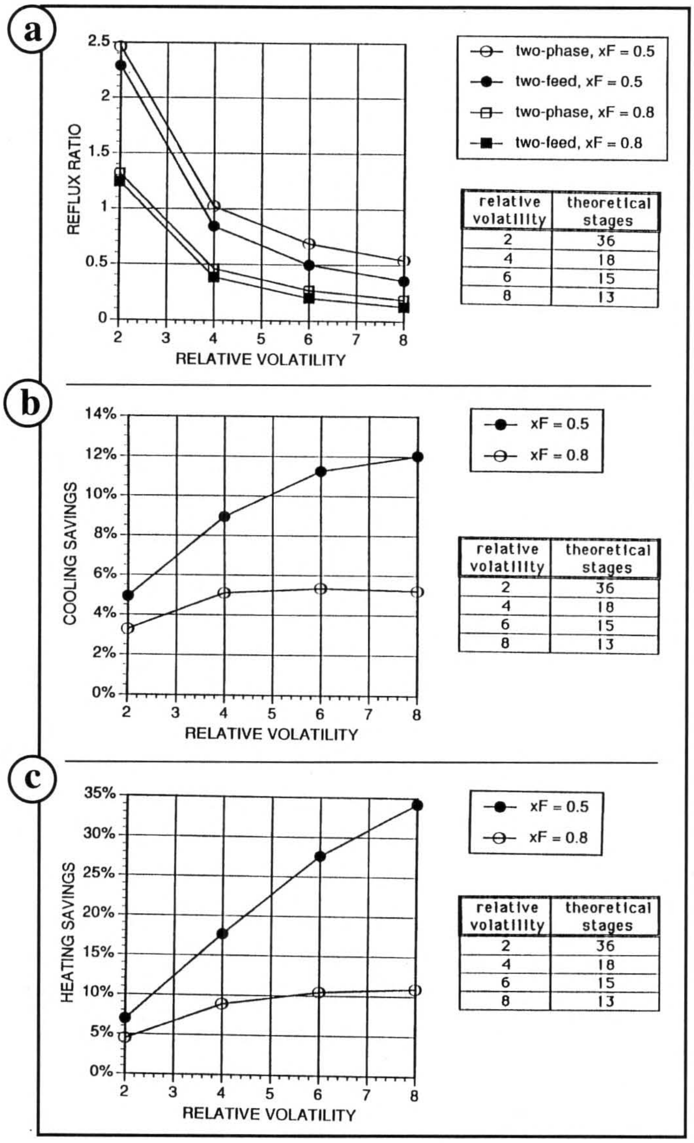

***Figure 4. (a)** Effect on reflux ratio of using two-enthalpy feed rather than two-phase feed for $x_D=0.99$, $x_B=0.01$, $q=0.5$. **(b)** Effect on cooling requirements of using two-enthalpy feed rather than two-phase feed for $x_D=0.99$, $x_B=0.01$, $q=0.5$. **(c)** Effect on heating requirements of using two-enthalpy feed rather than two-phase feed for $x_D=0.99$, $x_B=0.01$, $q=0.5$.*

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PART 6

SERVICE AND ADMINISTRATION

I considered adding "service" to the title of this paper, but I did not want to lose my credibility at the outset. Although it often seems like a black hole for effort, service and administrative positions can occasionally interact synergistically with research and teaching. Probably the main synergism is the people both inside and outside the university who one meets while serving on committees or as an administrator. There are often mutual research or teaching interests that can blossom into collaborations or even funding. This is particularly true of professional service in organizations such as to ASEE or AIChE.

A second benefit, particularly of administrative positions, is the acquisition of a much broader outlook. My experience as Head of Freshman Engineering was extremely useful when I was writing *Teaching Engineering.*[2] Contact with students and professors helped me see the similarities and differences in teaching engineering in the different engineering disciplines. This helped make *Teaching Engineering* a book for all engineering professors, not just for chemical engineering professors.

These examples within the university may seem farfetched. Serving as a journal editor, on the other hand, is normally directly related to one's own research. An editor who reads manuscripts in order to make editorial decisions is forced to keep up with the literature in his or her broad area of research. Without this extra incentive, I would read only the literature in my narrow area of specialization. My duties as an associate editor of *Chemical Engineering Education* have forced me to read and sometimes understand advances in chemical engineering outside of what I usually teach or research.

CLOSURE

Although teaching and research are often viewed as opposites, they often interact synergistically. Efforts to improve as a lecturer will at the same time improve both teaching lectures and research presentations. Learning because one needs to know something for classroom teaching or for research can be both effective and efficient. Once learned, the knowledge is then available for unexpected uses in research or teaching. Learning appears to be the major synergistic mechanism between teaching and research. Synergisms do occur between course teaching and research. The most obvious of these are when course projects blossom into research projects. Research results are often, quite deliberately, translated into a form that can be taught to graduate or undergraduate students.

ANSWER TO QUESTION: The sign on a term multiplying the equation was switching from plus to minus or vice versa. If both sides of the quadratic equation are multiplied by -1, the sign used for the solution switches.

NOMENCLATURE

a_p	surface area/volume of adsorbent, m^2/m^3
c_m	concentration in mobile phase, kg/m^3
C_s	concentration in stationary phase, kg/m^3
d_p	particle diameter, m
D	column diameter, m
f	fraction of solute in mobile phase, Eq. (1)
i	index for stage
k_m	lumped parameter mass transfer coefficient, m/s
K	permeability in Eq. (3)
K'	equilibrium constant, Eq. (1)
L	column length, m
L_{MTZ}	length of mass transfer zone in column, m
M	mass of solute in stage, kg
p	pressure, N/m^2
Q	volumetric flow rate, m^3/s
R_N	ratio of L/L_{MTZ} in new and old design, Eq. (7)
R_p	ratio of d_p in new and old designs, Eq. (4)
s	index for transfer step
t	time, s
T	temperature, °C
v	interstitial velocity in column, m/s
V_m	volume of mobile phase in stage, m^3
V_s	volume of stationary phase in stage, m^3
ε_e	external porosity
μ	viscosity, poise

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