

# Introduction to Chemical Engineering Computing

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## Introduction

Chemical engineers need to learn to use computer programs in order to do their assignments in school and be technically competent when they graduate. In the past, computer proficiency was obtained hit or miss, with too many students in the ‘miss’ category. An elective course was established in the Department of Chemical Engineering and given in Winter quarter, 2003, 2004, and 2005, to give beginning juniors a broad introduction to computers. They had already taken a computer science course their freshman year, so the new course concentrated on chemical engineering applications. This paper describes the course and gives a quantitative assessment of its impact in the Chemical Reactor Design class.

## Course Description

The Department of Chemical Engineering at the University of Washington uses Excel, Matlab, Simulink, AspenPlus, and FEMLAB. This paper describes a course introducing students to these programs, except for Simulink that is introduced in Process Control. For each topic (see Table I), a lecture hour outlined the method used to solve a class of problems and demonstrated specific techniques to do so. A handout gave the details each week. Then in the laboratory hour following, students worked in pairs to solve problems like those solved in class. In this hour they applied the techniques, and solved an interesting chemical engineering problem with the help of seniors who served as assistants. The laboratory problem was not turned in, and group work was allowed and encouraged. After the laboratory, a problem of the same type was assigned, and this problem was solved individually. The solution to this problem was checked. If the solution was incorrect, corrections and suggestions were given so that students could redo the problem. This was a great incentive to complete the assignments correctly, since homework with errors had to be corrected or it wouldn't count. (This is similar to real engineering work - you have to do it and redo it until it is right. No one wants the bridge to fall down, or the reactor to explode.) Credit was given to those students who (a) attended class and (b) turned in correct assignments of 8 of the 10 assignments. In the 2004 and latest, 2005, version of the course, a CoursePak was provided with worked examples and discussion<sup>2</sup>.

One philosophy that permeates the course is: **learn to check your work!** Many problems being solved today in industry are intractable with analytical methods. That is due to the widespread availability of desktop and laptop computers, but even more so due to the sophisticated software available today. Thus, engineers will probably be solving a problem that no one knows the answer to, and it is their job to insure the problem is posed correctly on paper

and in the computer. Then, it must be solved correctly, possibly with error estimates. The programs don't always work, and a student must recognize this and devise strategies for making it work. The bottom line is to convince someone you have a solution every bit as reliable as an analytical solution, although without the analytical form.

Naturally, the course content has evolved from the first time the course was offered. The topics covered during the January, 2004, offering are listed in Table I.

**Table I. Topics covered in 2004**

1. pVT using Excel
2. recycle systems with chemical reaction equilibrium using Excel
3. chemical reaction equilibrium using MATLAB
4. plug flow reactors using MATLAB
5. detailed models of single units using AspenPlus
6. process models using Aspen Plus
7. flow of a polymer between flat plates using MATLAB
8. flow of a polymer between flat plates using Excel
9. partial differential equations using MATLAB
10. flow of a polymer between flat plates using FEMLAB

As can be seen from the applications, the mathematical topics include nonlinear algebraic equations, initial value problems as ordinary differential equations, boundary value problems, partial differential equations in time and one space dimension, and partial differential equations in two space dimensions. Some of the problems are solved with multiple methods, so that the student can see how easy it is to use different methods, and what information must be supplied. For example, doing pVT calculations with Excel or MATLAB requires knowing critical constants and significant programming for multicomponent mixtures. AspenPlus, however, has that information readily available. The other important consideration, of course, is that Excel is readily available in all companies, whereas MATLAB, AspenPlus, and FEMLAB may not be. While these trade offs are discussed, the focus is on using the best method for the problem, since the major goal is to prepare the students to use the computer in their other courses, and they have access to all of them. Most of the topics listed in Table I have been covered in courses the students have taken or are taking concurrently. The exception is the plug flow reactor problem. Some rudimentary description of a plug flow reactor is necessary in this case, but the students generally have sufficient background in mathematics to understand the problems. The last topic, 2D flow, goes beyond what is normally covered in the Transport Course, which is taught concurrently but is limited to simple problems that can be solved analytically.

During the 2004 version of the course, FEMLAB was introduced in the last week. Most of the students by that time had completed the course with their 8 correct assignments, so that there was no need to attend either lecture or laboratory. However, the entire class was there. After handing out a one-page instruction sheet and demonstrating the program, the class ended. While the instructor was putting the projector and computer away, the students went to the laboratory and began work. Ten minutes later, the instructor entered the lab and walked down the row of computers. Lo and behold, nearly every student had solved a 2D flow problem for a

Newtonian fluid and had a multicolored plot on the screen. It was at that time that the author decided to switch the focus of some of the assignments for the 2005 version of the course.

Boundary value problems can be solved in Excel, in MATLAB, and they can also be solved using shooting methods in MATLAB. In 2004, a finite difference method using Excel and a shooting method using MATLAB were presented for boundary value problems. In 2005, those methods were discarded and replaced with FEMLAB. While it is true that a small consulting office may not have FEMLAB and an engineer would have to program Excel or MATLAB to solve these problems, the goal of the course is educational: learn the chemical engineering with the computer as a tool, not an end in itself. The same decision was made for partial differential equations in time and one space dimension. FEMLAB works quite nicely for those problems, too. The final problem was a significant polymer flow problem in two dimensions. Maybe this was too hard, but with help the students needing the assignment were able to complete it.

### Sample Problems

Shown in Tables II-V are several one/two-page handouts that were provided to the class. They illustrate the objectives of the lecture hour, the laboratory hour, and the assignment to be done outside of class. The first time a program was used, the problems done in class, lab, and on assignments were simple; the next time the program was used the problems were more difficult. Table II gives a simple problem to solve the cubic equation of state for a mixture at high pressure using Excel. Table III gives a problem involving chemical reaction equilibrium using MATLAB. Table IV asks students to use AspenPlus to solve mass and energy balances for a process with recycle, chemical reaction equilibrium, and phase equilibrium. Table V gives a transient one-dimensional flow problem, which was solved in 2004 using MATLAB, but in 2005 it was solved using FEMLAB. The handout for learning to use FEMLAB is in Table VI.

**Table II. Ch.E. 375 W, '04 - Assignment One**  
Computer Tools/Skills in Chemical Engineering

Course web site: <http://courses.washington.edu/checomp/>  
Course listprocess (send e-mail to entire class): [chem\\_e375a\\_wi04@u.washington.edu](mailto:chem_e375a_wi04@u.washington.edu)

**Class:**

Introduction

Summary of equations of state

Single nonlinear equations in Excel

Excel hints

Problem: Find the molar volume of ammonia gas at 56 atm and 450 K using the Redlich-Kwong equation of state,  $a = 4.2527$ ,  $b = 0.02590$ ,  $p_c = 111.3$  atm,  $T_c = 405.5$  K; units of  $a$  and  $b$  correspond to  $v$  in liter / g mol.

**Laboratory problem**

Find the molar volume of ammonia gas at conditions from 50 to 250 atm and 400 to 800 K using the Redlich-Kwong equation of state. Plot the molar volume in a 3D plot and a contour plot. (The plotting part of this was too hard for the first assignment.)

**Assignment One**

Consider a mixture of 25% ammonia, the rest nitrogen and hydrogen in a 1:3 ratio. The gas is at 270 atm and 550 °K. Compute the specific volume using:

- (a) ideal gas law;
- (b) Redlich-Kwong equation of state;
- (c) Soave-Redlich-Kwong equation of state.

Where did you get the data you needed? How do the three answers compare? Is the gas ideal or not? Comment.

**Table III. Ch.E. 375, W, '04 - Assignment Three**  
Computer Tools/Skills in Chemical Engineering

**Class:**

Review homework  
Equilibrium reactions  
Use of MATLAB

**Laboratory problem**

Model the equilibrium reactor that we did in the last assignment. The feed rate to this part of the process is (k mol/hr): CO: 630, H<sub>2</sub>: 465, CO<sub>2</sub>: 69, steam: 986. The K value is 399.6. Determine the molar flow rates leaving the reactor, which is an equilibrium reactor. Compute the molar flow rates out using MATLAB.

**Assignment Three**

Use MATLAB to find the molar flow rates of all species out of an equilibrium reactor when the inlet values of nitrogen, hydrogen, and ammonia are 1.1, 3, and 0.2. The equilibrium constant is 0.06 at 589 K, and use 220 atm.

$$K = \frac{p_{\text{NH}_3}^2}{p_{\text{N}_2} p_{\text{H}_2}^3} = \frac{y_{\text{NH}_3}^2}{y_{\text{N}_2} y_{\text{H}_2}^3} \frac{1}{p^2}$$

**Table IV. Ch.E. 375 Special Topics, W, '04 - Assignment Six**  
Computer Tools/Skills in Chemical Engineering

**In-class problem**

Go over the homework

Learn how to use AspenPlus to solve problems with recycle streams.

**Laboratory problem**

Solve the same problem as given in Assignment Six below, except use a simple reactor with a 87% conversion (Rstocic block) and use simple splitters (Sep2 blocks) for all the separation units: the condenser separates all the water (and only water), the Rectisol process separates all the carbon dioxide (and only that), and the pressure swing adsorption unit is a perfect separation for hydrogen and carbon monoxide. The carbon monoxide is recycled.

**Assignment Six**

One of the senior design groups in Spring, 2003, designed a process to make hydrogen from coal. Coal was used because the US has over 200 years supply of coal, and the hydrogen was to be used in fuel cells to run the buses in Seattle. Model the following part of the process.

The feed rate to this part of the process is (lb mol/hr): CO: 1260, H<sub>2</sub>: 932, CO<sub>2</sub>: 140, steam: 1972, at 350 °F and 20 psia. The stream goes to a reactor which is an equilibrium reactor, and the stream exits in chemical equilibrium at 710 °F. Then the stream goes to a condenser at 80 °F, which removes most of the water, and to a Rectisol process, which removes all the carbon dioxide. Finally, the carbon monoxide and hydrogen are separated in a pressure swing adsorption unit, and the carbon monoxide is recycled. In the process done for class, the carbon monoxide was sent to a combustor.

Model the process using an equilibrium reactor, the RGibbs block. Aspen will compute the equilibrium conditions for you (K values, Gibbs free energies, and the equilibrium conditions). A flash separation (Flash2 block) is adequate to model the condenser. Use a simple splitter (Sep2 block) for the Rectisol process (assume perfect separation: removal of carbon dioxide and water). The pressure swing adsorption unit should be run (using a simple splitter, the Sep block) so that the concentration of carbon monoxide in the hydrogen output stream is less than 100 ppm (for fuel cell use). Construct the mass and energy balances for this process.

Your report should have a flow sheet, give the mass balances and flowsheet information, and examine (and report) on the reasonableness of your results. Indicate how you proceeded to meet the design conditions. Your report should be all in one file; please have your first name in the name of the file.

**Table V. Ch.E. 375, W, '04 - Assignment Nine**  
Computer Tools/Skills in Chemical Engineering

**In-class problem**

Go over the homework

Learn how to use Malab to solve partial differential equations in one space dimension.

**Laboratory problem**

Go through the steps in the CoursePak, p. 101, *et seq.* You can plot all temperature values versus time, but it is more instructive to plot them versus distance, with time as a parameter. Use

```
tspan = [0:100:500]
x = [0:0.2:1]
after solving the problem for y, using ode45, use
for itime=1:6
    for nopoint=1:5
        yplot(nopoint,itime) = y(itime,nopoint)
    end
    yplot(6,itime) = 0. %the boundary value for the 6th point
end
plot(x,yplot(:,1),'o-',x,yplot(:,2),'x-',...)
```

**Assignment Nine**

Consider the flow of a Newtonian fluid between two flat plates, starting at rest, with one plate being moved at time zero. The governing equations are on p. 117 of “Transport Phenomena”<sup>1</sup>

$$\rho \frac{\partial v}{\partial t} = \mu \frac{\partial^2 v}{\partial x^2}$$

$$v(x,0) = 0$$

$$v(0,t) = v_0 \text{ and } v(H,t) = 0 \text{ for } t > 0$$

Solve this problem for  $v_0 = 0.03$  m/s,  $H = 0.005$ ,  $\mu = 1180$  Pa s,  $\rho = 800$  kg/m<sup>3</sup>. Use six points in the x direction (including the boundary points). Plot the results versus time. You can plot all velocity values versus time, but it is more instructive to plot them versus distance, with time as a parameter. (This isn't required, though.) Naturally, you need to verify that your right-hand side is correct. Since this is a linear problem, this is one case where you could compare your numerical solution to the analytical one, Eq. (4.1-40) of “Transport Phenomena”<sup>1</sup>.

## Table VI. Tutorial for using FEMLAB to solve elliptic boundary value problems

**open** - open Matlab and give the command **femlab**;  
- choose a 1D, 2D, or 3D button, and then choose the equation from the list of equations;  
(double click on the + to see the subheadings)  
or  
- select cancel in the Model Navigator and open a previous solution.

**draw** - Choose Draw; to make a rectangle with a rectangular hole in it:  
- click on the square icon, move to the screen and drag and draw a rectangle;  
- for the inner rectangle, do again;  
- double click on the object to set exact dimensions;  
- to make a hole, choose Draw/Composite Object, select both R1 and R2, use R1 – R2.

**mesh** - click once on the triangle icon  
- click on divided triangle icon to refine the mesh

**subdomain/subdomain settings** - to check the differential equation and set the parameters

**boundary mode** - choose  $\partial W$  icon or boundary/boundary mode  
- click on one boundary or select a number in the window  
- set the boundary conditions - the equation is given, select parameters for the equation

**solve/solve problem or =** to solve the problem

**post/plot parameters** - set parameters to choose the type of plot  
- If you want detailed information about the solution, you can use subdomain integration to integrate a variable or expression over the domain; boundary integration to integrate over a boundary segment; you can integrate anything you can write an equation for.

You can go back and refine the mesh (click the more refined mesh symbol) and resolve the problem. This gives you an indication of the accuracy of the solution.

**Save your work frequently!** - save as a xxx.mat file for easy restart. (m-files save all your commands, including mistakes.)

(This is for FEMLAB version 2.3, used in Winter, 2004)



## Quantitative Assessment

The course is an elective course which is constrained by class schedules and other classes using the computer laboratory. Thus, every junior isn't able to take the class. Despite that, the enrollment has grown from year to year, as shown in Table VII. The total number of juniors in 2003 and 2004 was about the same (44), and the number in 2005 is larger (70). When comparing grade point averages (of all chemical engineering courses at the end of their junior year), in the first year those taking the course had a higher grade point average (GPA) (+0.27), but in the second year the difference was insignificant. As would be surmised by the gradually increasing enrollment, the student evaluations were generally positive. The first year the students asked for more written material, which was provided in the second year.<sup>2</sup> The second year they asked for more student helpers, which had been limited that year because of schedule conflicts with the seniors' schedule. The average time spent per week, including the time in class and laboratory was 2.9 hours in 2003 and 4.1 hours in 2004 (self-reported). Two quarter credits were given for the course on a credit/no-credit basis.

**Table VII. Enrollment in Ch.E. 375, "Introduction to Chemical Engineering Computing"**

Enrollment in 375	2003	2004	2005
Ch.E.	16	26	43
other	2	3	4
total	18	29	47
Ch.E. GPA			
Those taking 375	3.02	3.12	
Those not taking 375	2.75	3.13	
All students	2.83	3.13	

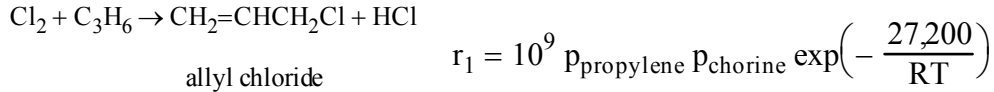
A limited, quantitative evaluation is provided by an examination of scores on test problems in the Chemical Reactor Design course taken 6 months later. All students taking the Chemical Reactor Course receive instruction in solving ordinary differential equations for plug flow reactors and transient stirred tank reactors. Quantitative measures are reported comparing performance by students who elected to take the computing class and those that didn't. These groups were further divided into male and female cohorts.

In 2003, one-half of the Reactor Design final examination was to design a sophisticated reactor on the computer. The students were told ahead of time that they would have a reactor design problem with multiple reactions and energy effects, so that they could prepare their template computer program. They were then given one hour in the computer laboratory to solve the problem described in Table VIII. A summary of the types of errors made is given in Table IX. In 2004, it wasn't practical to give a test on the computer since the final was given in a building far away from the laboratory and the computer support person was unavailable. It was too risky to try a 'hands-on' final with no one there to resolve computer problems. However, two questions (2b and 2c in Table X) on the final were very computer related, and the cumulative scores on these two problems are used in the evaluation.

**Table VIII. Ch.E. 465 - Final Exam, Part II**

Dec. 16, 2003, Open Book and Open Notes and Computer Available

(50/100). Consider the reaction of propylene and chlorine to form allyl chloride.



The rate is in kg.mol/m<sup>3</sup>s, the temperature is in °K, and the pressure is in atm, and the activation energy is in cal/gmol °K. The heat of reaction is -117,000 kJ/kgmol, and the average heat capacity can be taken as constant at 104 kJ/kgmol °K. The pipe diameter is 0.0254 m, its length is 8 m, and the heat transfer coefficient is 0.284 kJ/m<sup>2</sup> °K s. The total feed rate is 1.07 x 10<sup>-4</sup> kg.mol/s, and the ratio of propylene to chlorine is 2.5. The inlet conditions are 500 °C and 2.72 atm, the surrounding temperature is 500 °C, and the pressure is constant in the reactor. The reaction is carried out in the gas phase which is flowing in an empty tube. The energy equation is:

$$F_t C_p \frac{dT}{dV} = -U \frac{2}{R} (T - T_{\text{surroundings}}) + r_1 (-^2 H_{\text{rxn}})$$

- (a) Write a computer code to model this reactor (print the final code).
- (b) Test your computer code to insure it is correct. Explain what tests you have done and why you think the code solves the problem above.
- (c) Run the code and plot all the molar flow rates versus volume; plot the temperature versus volume.

**Table IX. Errors in Part II of Final, Ch.E. 465, 2003**

Chemical Engineering Errors (55)

Keeping partial pressure the same throughout the reactor (12)  
Used the gas constant in place of the tube radius (8)  
Left out one or two of the product flow rates (7)  
Used a constant temperature in kinetic constant (5)  
Used wrong gas constant (5)  
Didn't compute partial pressure correctly (4)  
Left out the cooling term (4)  
Used wrong cooling temperature (2)  
Units wrong for partial pressure (2)  
Left out the equations for mass/mole changes (2)  
Used  $2/R = 1/D$   
Used wrong sign for heat generation term  
Flow rates (mol/time) were adjusted for temperature  
Multiplied rather than divided by flow rate x heat capacity

Computer Programming Errors (13)

Switching t and y in ode solver (2)  
Use T rather than y(5) or some such (2)  
Had some code that had no effect on the solution (2)  
Used variables that weren't defined (didn't come into the subroutine) (2)  
Used only part of flow rate when computing flowrate x heat capacity  
Commands in wrong order  
Use E rather than exp( )  
Used | rather than +  
Evaluated the rate using the rate (didn't understand ODEs)

**Table X. Ch.E. 465 - Final Exam, Dec. 15, 2004**  
Open Book and Open Notes

(55/100) 2. The equations for free-radical polymerization derived in class were

$$\frac{d[I]}{dt} = -k_d[I], \quad \frac{d[C_2H_2]}{dt} = -2k_g[C_2H_2]^2$$

$$\frac{d[M]}{dt} = -k_p[M] \sqrt{\frac{k_d[I] + 2k_g[C_2H_2]^2}{k_t}}$$

The values of the kinetic parameters and initial conditions are

$$k_d = 1.82 \times 10^3 \text{ sec}^{-1}, k_g = 6.24 \times 10^2 \text{ cm}^3 \text{ gmol}^{-1} \text{ sec}^{-1} \quad [I]_0 = 3e-7 \text{ gmol/cm}^3$$

$$k_p = 4.08 \times 10^3 \text{ cm}^3 \text{ gmol}^{-1} \text{ sec}^{-1}, k_t = 1.51 \times 10^8 \text{ units?} \quad [C_2H_2]_0 = 0.01 \text{ gmol/cm}^3$$

$$[M]_0 = 0.04 \text{ gmol/cm}^3$$

a. (10) What units must  $k_t$  be expressed in?

b. (20) Prepare a right-hand side for a MATLAB program that will integrate these equations in time.

The calling statement will be only:

$$[t \ y] = \text{ode45}(\text{'prob3'}, [0 \ 100], [3e-7 \ 0.01 \ 0.04]),$$

where the time is in seconds and the concentrations are in  $\text{gmol/cm}^3$  for initiator, acetylene, and monomer. All other numbers should be in the prob3.m.

c. (25) The format of prob3.m is function ydot=prob3(t,y). Provide numbers for t and y that you can use to test your code, and give the expected outcome.

The scores on the Final Exam (Table VIII, 50 points maximum) and grades in the Reactor Design Course in 2003 are given in Table XI. The scores on the Final Exam (Table X, 2b, 2c, 45 points maximum) and grades in the Reactor Design Course in 2004 are given in Table XII.

**Table XI. Assessment of Computing Course in 2003**

	Number	ChE GPA	Score on Final	Reactor Design Grade
Women				
taking 375	10	3.23	39.0	3.36
not taking 375	10	2.81	36.0	3.08
all women	20	3.02	37.5	3.22
Men				
taking 375	6	3.10	35.0	3.20
not taking 375	18	2.96	38.3	3.18
all men	24	2.99	37.5	3.18
Female and male				
taking 375	16	3.18	37.5	3.30
not taking 375	28	2.91	37.5	3.14
All students	44	3.01	37.5	3.20

**Table XII. Assessment of Computing Course in 2004**

	Number	ChE GPA	Score on Final	Reactor Design Grade
Women				
taking 375	10	3.05	43.6	3.55
not taking 375	3	3.15	36.0	3.13
all women	13	3.07	41.9	3.45
Men				
taking 375	9	3.21	41.6	3.49
not taking 375	21	3.13	40.7	3.46
all men	30	3.16	41.0	3.47
Female and male				
taking 375	19	3.12	42.6	3.52
not taking 375	24	3.13	40.1	3.42
All students	43	3.13	41.2	3.46

Consider first Table XI. The first striking feature is that 50% of the eligible women took the class but only 25% of the eligible men did so. Those taking the class generally had higher chemical engineering grade point averages, with a differential of +0.42 for the women and +0.14 for the men, and +0.27 for all students. Next look at the scores on the “hands-on” final examination for Chemical Reactor Design. The women students taking the computer class did better than those not taking the computer class, whereas the differential was reversed for the men. For both women and men, the course grade for Chemical Reactor Design was higher for the students taking the computer class than for those not taking it, but the differential was not very different from the differential in their chemical engineering GPAs. Thus, it is difficult to

argue that the 2003 version of the class helped the students on these aspects of their Chemical Reactor Design course.

When evaluating the 'hands-on' part of the final exam, 2003, Table IX, it is surprising that most of the errors (81%) were what the author calls 'chemical engineering errors' rather than computing errors. These errors would affect any problem, whether done on the computer or not. This is particularly important in Chemical Reactor Design, since errors setting up the problem can cause huge, and unrecoverable, errors due to the Arrhenius rate expression. The author has tried, with limited success, to impress this point onto students in the Reactor Design class.

Next consider Table XII, which was for the 2004 year. In this version of the computing class, a CoursePak was provided<sup>2</sup>, and lessons from the first presentation of the course were incorporated in the class. This time 77% of the eligible women took the computing class, but only 30% of the eligible men did so. Among the women, those taking the computer class had a slightly lower chemical engineering GPA than those not taking it (-0.1), whereas among the men, the differential was reversed (+0.08). Both values are small and probably insignificant. Next look at the scores on the final examination questions, 2b and 2c, Table X. The women who had taken the computing class scored significantly above the women who didn't. Their point average was 21% higher. This translated into a differential in the Chemical Reactor Course grade of +0.42, even though their chemical engineering GPA was 0.1 lower. Thus, taking the class caused their Chemical Reactor Course grade to be 0.5 higher than their GPA (maximum GPA 4.0). For the men, those having taken the computing class scored about 2% higher than those who didn't, and this number is comparable to the differential in their chemical engineering GPA.

## Conclusion

A course to introduce chemical engineering students to computing tools they will use in their education has been successfully introduced. Interestingly, a large fraction of the women students take the elective course, whereas only a small fraction of the men students take the course. During the second offering of the course, the women who took the course did significantly better in the Chemical Reactor Design course two quarters (and a summer) later.

## Nomenclature

a	constant in Redlich-Kwong equation of state
b	constant in Redlich-Kwong equation of state
$[C_2H_2]$	concentration of acetylene
$C_p$	heat capacity
$F_t$	total molar flow rate
H	distance between plates
$-\Delta H_{rxn}$	heat of reaction
[I]	concentration of initiator in polymer reaction
$k_d, k_g, k_p, k_t$	rate constants in polymer reaction
K	chemical reaction equilibrium constant
[M]	concentration of monomer in polymer reaction
$p_c$	critical pressure of a chemical
$p_i$	partial pressure of i-th species
p	total pressure
$r_1$	chemical reaction rate
R	gas constant or radius of pipe
t	time
$T_c$	critical temperature of a chemical
$T_{surr}$	temperature of surroundings
U	overall heat transfer coefficient
v	velocity
$v_0$	velocity of plate
V	reactor volume
x	spatial position
Greek symbols	
$\rho$	density
$\mu$	viscosity

## Bibliographic Information

<sup>1</sup> Bird, R. B., W. E. Stewart, E. N. Lightfoot, "Transport Phenomena", 2<sup>nd</sup> ed., Wiley, New York, 2002.

<sup>2</sup> Finlayson, B.A., "Introduction to Chemical Engineering Computing", CoursePak, University of Washington, 2003, 2004, book in progress.

## Biographical Information

### BRUCE FINLAYSON

Bruce Finlayson is the Rehnberg Professor of Chemical Engineering at the University of Washington, where he has taught for 38 years. He obtained a B.A. and M.S. from Rice University in 1961 and 1963, respectively, and a Ph.D. from the University of Minnesota in 1965. He then served two years in the U.S. Navy. He was chair of the Department of Chemical Engineering from 1989-1998, is a member of the National Academy of Engineering, and was President of the American Institute of Chemical Engineers in 2000. He was Director of the ASEE Summer School for Chemical Engineering faculty in 1997, and was the winner of the Joseph J. Martin Award of the Chemical Engineering Division of ASEE in 1994.