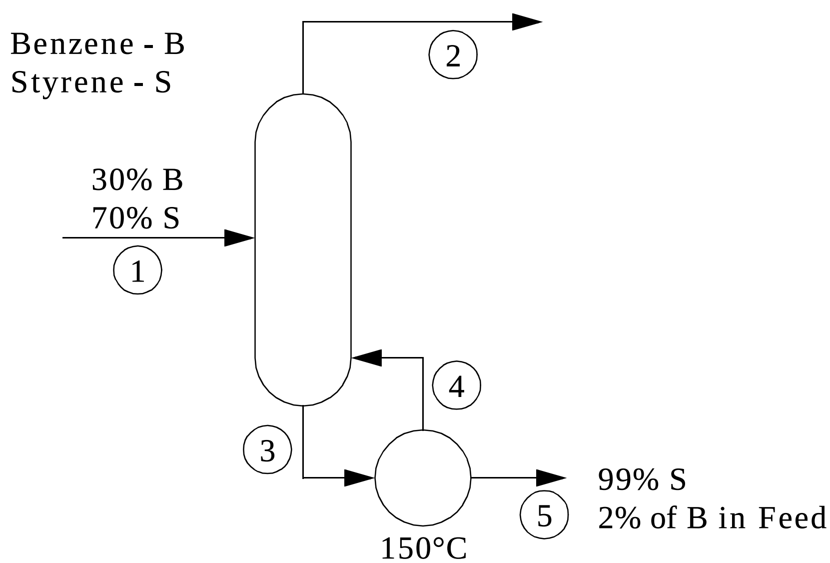
Problem 6.46 Using Excel as a Calculator

A liquid mixture containing 30.0 mole% benzene and 70.0 mole% styrene is to be separated in a distillation column. The column produces an overhead product (distillate) and a bottoms product. The bottoms product is 99 mole% styrene and contains 2.0% of the benzene fed to the column.

The liquid stream leaving the bottom of the column (not the bottoms product) goes to a partial reboiler, in which a portion of it is vaporized at 150°C and returned to the bottom of the column. The residual liquid from the reboiler is the bottoms product. The vapor and liquid streams exiting the reboiler are in equilibrium. The boilup ratio, or mole ratio of the vapor and liquid streams leaving the reboiler, is 2.5:1. Using Raoult's law where appropriate, calculate the compositions (component mole fractions) of the distillate product, the vapor returned to the column from the reboiler, and the liquid feed to the reboiler, and estimate the required operating pressure of the reboiler.

First we'll draw the PFD and label the streams



Next we'll pick a basis

$$n_1 = 100 \text{ mol/h}$$

so

$$n_{1_B} = x_{1_B} n_1 = 0.3(100) = 30$$

$$n_{1_S} = x_{1_S} n_1 = 0.7(100) = 70$$

Treating the overall system as a separator, we're given the split fraction of B in Stream 5

$$t_{5_B} = 0.02$$

so that

$$t_{2_B} = 1 - t_{5_B} = 1 - 0.02 = 0.98$$

and

$$n_{5_B} = t_{5_B} n_{1_B} = 0.02(30) = 0.6$$

$$n_{2_B} = t_{2_B} n_{1_B} = 0.98(30) = 29.4$$

From the definition of mole fraction we have

$$n_5 = \frac{n_{5_B}}{x_{5_B}} = \frac{n_{5_B}}{1 - x_{5_S}} = \frac{0.6}{(1 - 0.99)} = 60$$

and

$$n_{5_S} = x_{5_S} n_5 = 0.99(60) = 59.4$$

Now by an overall mass balance on S

$$n_{2_S} = n_{1_S} - n_{5_S} = 70 - 59.4 = 10.6$$

So the distillate compositions are given by

$$x_{2_B} = \frac{n_{2_B}}{n_2} = \frac{29.4}{(29.4 + 10.6)} = 0.735$$

$$x_{2_S} = 1 - x_{2_B} = 1 - 0.735 = 0.265$$

From the problem statement Stream 4 is a vapor stream in equilibrium with the liquid Stream 5. We know T and the x_i's, and we need to calculate P and the y_i's, so we need to do a BUBL P calculation. For a BUBL P

$$P = \sum x_k p^*_k$$

and

$$y_k = \frac{x_k p^*_k}{P}.$$

To find p^*_k we'll use the Antoine equation

$$\log_{10}(p^*) = A - \frac{B}{T + C}$$

with T in °C and p^* in mm Hg.

For B

$$A = 6.90565,$$

$$B = 1211.033,$$

and

$$C = 220.790$$

For S

$$A = 6.92409,$$

$$B = 1420.0,$$

and

$$C = 206$$

From the Antoine equation and the BUBL T calculation, we'll know y_{4_S} and y_{4_B}. From the definition of the boilup ratio

$$n_4 = 2.5 n_5$$

and

$$n_{4_S} = y_{4_S} n_4,$$

$$n_{4_B} = y_{4_B} n_4.$$

Once these flows are known a mass balance around the reboiler gives

$$n_{3_S} = n_{4_S} + n_{5_S},$$

$$n_{3_B} = n_{4_B} + n_{5_B}.$$

And the composition of the reboiler feed is calculated by the usual definitions.

By and large *Excel* serves as a way to keep track of the calculations in this problem. There aren't too many speed shortcuts for this problem. The finished spreadsheet looks like:

T	*150*	°C				
Species	A	B	C	log10p*	p*	
Benzene	*6.90565*	*1211.03*	*220.79*	3.63956	4360.75	mm Hg
Styrene	*6.92409*	*1420*	*206*	2.93533	861.64	mm Hg
	Stream 1	Stream 2	Stream 3	Stream 4	Stream 5	
n B	30	29.4	7.89523	7.29523	0.6	
n S	70	10.6	202.105	142.705	59.4	
n tot	*100*	40	210	150	60	
x B	*0.3*	**0.735**	**0.0376**	**0.04863**	0.01	
x S	*0.7*	**0.265**	**0.9624**	**0.95137**	*0.99*	
t2 B	0.98		P	**896.631**	mm Hg	
t5 B	*0.02*		Boilover	*2.5*		
t2 S	0.15143					
t5 S	0.84857					

Nomenclature: In a spreadsheet, the cells containing entries that can be changed are in *italics*, the intermediate calculated quantities are in plain text, and the answers are in **bold text**.

If you are running this tutorial in *FrameMaker* and you have *Microsoft Excel* available, you can double-click the spreadsheets above and below and they will operate just like in *Excel*.

The formulas that are entered into the cells are:

T	*150*	°C				
Species	A	B	C	log10p*	p*	
Benzene	*6.90565*	*1211.033*	*220.79*	=B3-C3/(D3+$B$1)	=10^E3	mm Hg
Styrene	*6.92409*	*1420*	*206*	=B4-C4/(D4+$B$1)	=10^E4	mm Hg
	Stream 1	Stream 2	Stream 3	Stream 4	Stream 5	
n B	=B11*B$10	=B14*B8	=E8+F8	=E11*E$10	=B15*B8	
n S	=B12*B$10	=B16*B9	=E9+F9	=E12*E$10	=F12/F11*F8	
n tot	*100*	=SUM(C8:C9)	=E10+F10	=E15*F10	=SUM(F8:F9)	
x B	*0.3*	**=C8/C$10**	**=D8/D$10**	**=F11*F3/$E$14**	=1-F12	
x S	*0.7*	**=C9/C$10**	**=D9/D$10**	**=F12*F4/$E$14**	*0.99*	
t2 B	=1-B15		P	**=F11*F3+F12*F4**	mm Hg	
t5 B	*0.02*		Boilover	*2.5*		
t2 S	=1-B17					
t5 S	=F9/B9					

There are a number of techniques for entering formulas that speed entry immensely. First, you should (almost) never enter a cell reference by hand. For example, in cell D8 the formula reads “=E8+F8”. You enter this formula by clicking on cell D8, typing “=”, clicking on cell E8, typing “+”, clicking on cell F8, and finally pressing the *Enter* key.

The second is autogeneration of a series. To label the streams as “Stream 1” through “Stream 5”: Click on cell B7 and enter “Stream 1”. You should see a small black handle in the bottom right corner. Click and drag the little black handle to the right and *Excel* will automatically autofill the labels to “Stream 5”.

The third is similar. Click on cell C11. Type “=”. Click on cell C8. Type “/”. Click on Cell C10. Click on the formula entry bar between the C and the 10. Type a “$” and press *Enter* (The “$” is an *Absolute Reference* symbol. It means “Refer to the cell in row 10 no matter where the cell is copied-and-pasted or dragged”). Click and drag the little black handle to the right (to cell D11) and then down (to cell D12) and *Excel* will automatically calculate the compositions in Stream 2 and Stream 3.

The real value of *Excel* for a problem like this is not in the solution of the original problem but in the exploration of what happens for different requirements. For example, it is very common to specify a pressure for the reboiler. Suppose the problem had specified the reboiler pressure as 1000 mm Hg, and asked for the temperature, with all other specifications the same. With the present spreadsheet and *Excel’s Goal Seek* command we can solve that problem. In *Excel* (not in the tutorial object, because we need access to the menus) click on the *pressure* cell, E14. Under the *Tools* menu choose *Goal Seek*. The *Set cell:* box should say E14. Click in the *To value:* box and type 1000 (or whatever pressure you desire). Click in the *By changing cell:* box and then click the temperature box on the spreadsheet, B1. When the box shows “$B$1”, click *OK* or press *Enter*. The temperature should change to 154.325 and the *Goal Seek Status* box should appear. If you like your new temperature, click *OK* or press *Enter*. If you don’t, click *Cancel*. *Goal Seek* can easily find any temperature for pressures between 200 torr and 2000 torr.

Another *What If* scenario could be to see how the reboiler pressure and the vapor composition change with temperature. We do this by creating a *data table*. The detailed instructions are in *Excel’s* on-line help under *Create a one-variable data table*.

First we create a column of temperatures to check by using the *Fill->Series* command under the *Edit* menu. Then, one row above the first temperature and in the columns to the right we enter formulas to display the items of interest. Next select all of the cells in the table. Then choose *Table* under the *Data* menu. In the dialog box, click in the Column input cell: box. Then click on the temperature box in the spreadsheet, B1, and click *OK* or press *Enter*. *Excel* generates our table for us. If you want to get fancy you can graph the table using the *Chart Wizard*. The finished table and graph look like:

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x S	*0.7*	**0.265**	**0.9624**	**0.95137**	*0.99*

t2 B	0.98		P	**896.631**	mm Hg
t5 B	*0.02*		Boilover	*2.5*	
t2 S	0.15143				
t5 S	0.84857				

T	P	x B in 3
	896.631	0.0376
100	203.701	0.05021
110	284.283	0.04699
120	388.844	0.04418
130	522.183	0.04171
140	689.555	0.03953
150	896.631	0.0376
160	1149.47	0.03587
170	1454.45	0.03433
180	1818.25	0.03294
190	2247.78	0.03168
200	2750.13	0.03054