EngrD 2190 – Lecture 26

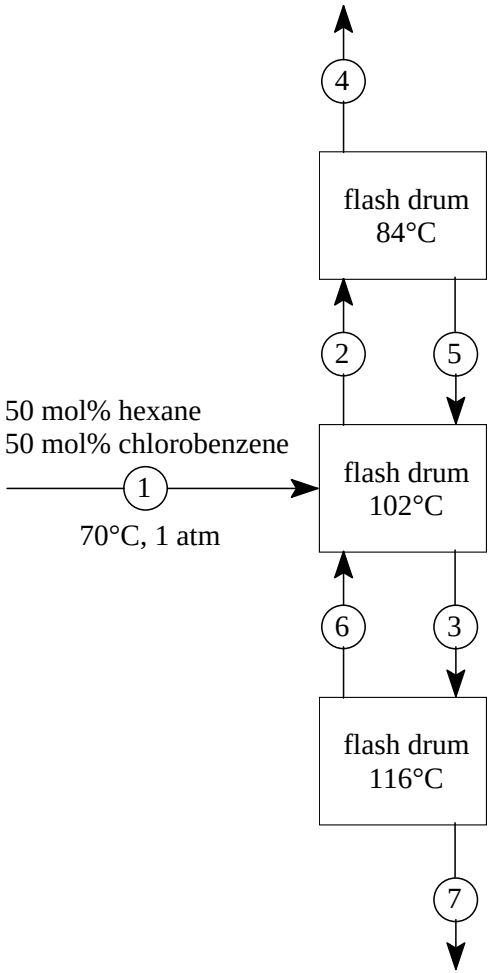
Concept: Graphical Mass Balances –
Operating Lines for Distillation

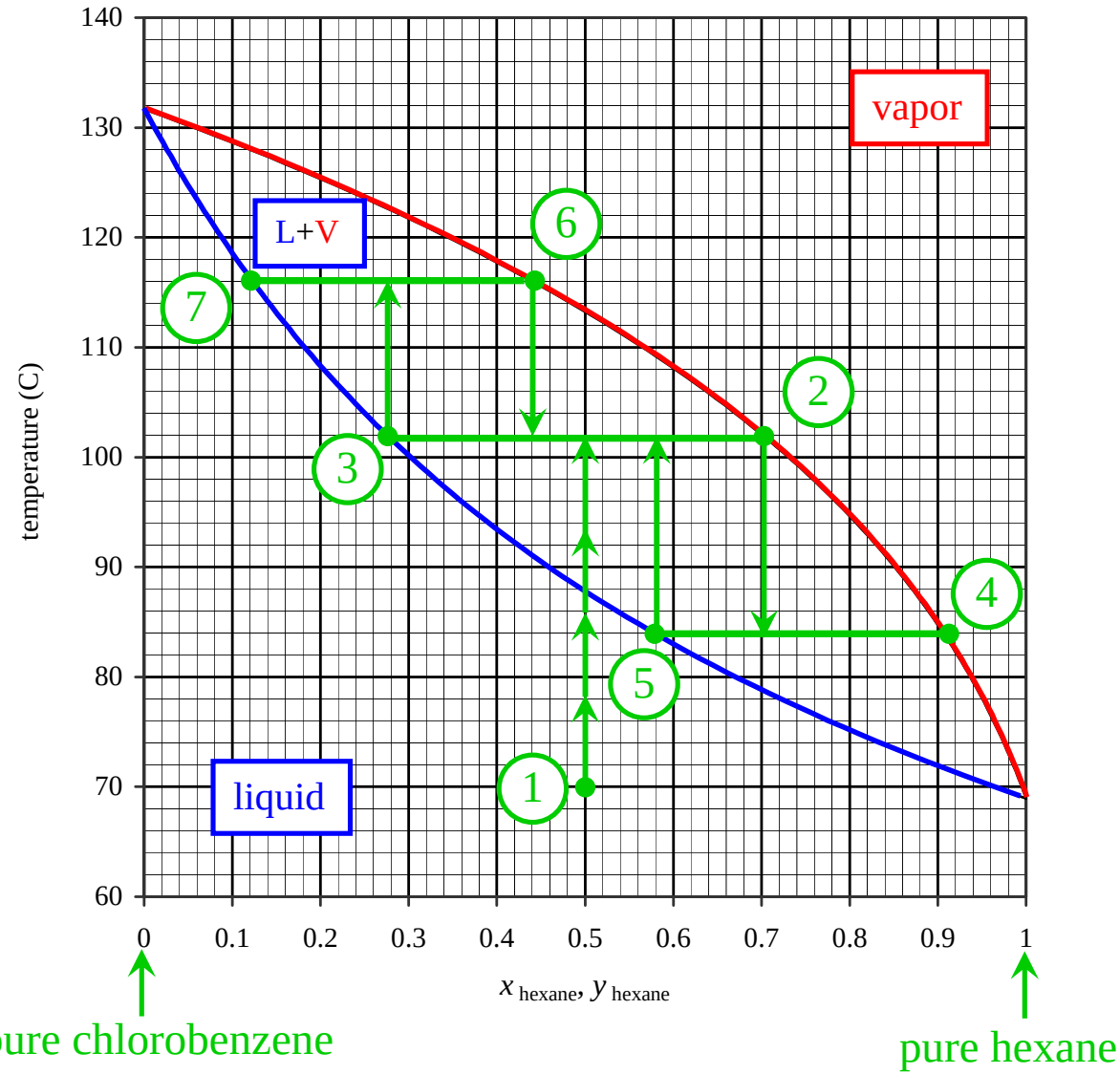
Context: Multistage, Counter-Current Flash Drums

Defining Question: How is a reboiler different from a boiler?

Bring a Straightedge or Ruler to Lecture 27.

Review: Single-Stage Flash Drums





Conservation of Energy requires F_{liquid}/F_{vapor} ratio must be the same for each equilibrium stage.

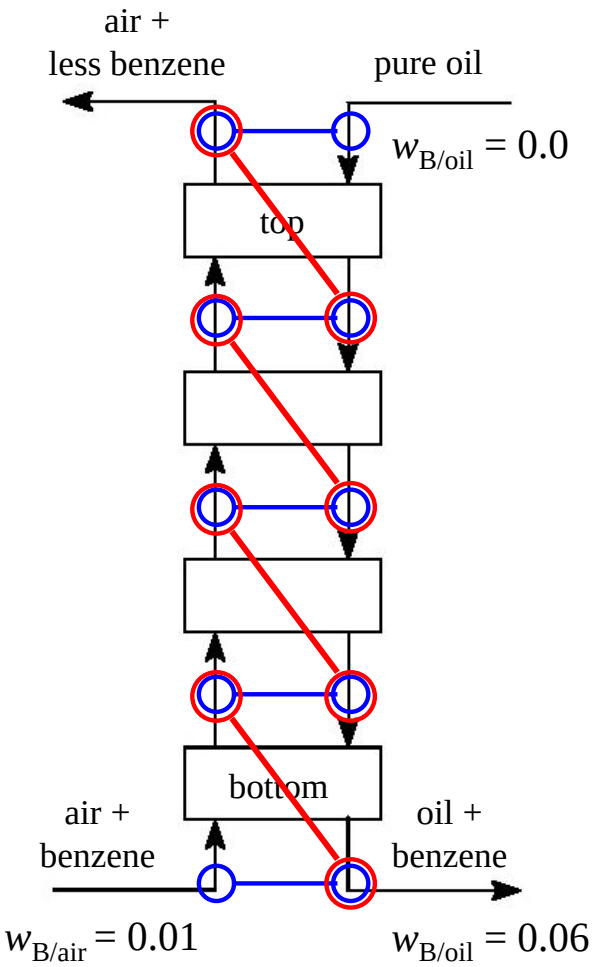
Recycle streams complicate lever rule calculations; must iterate.

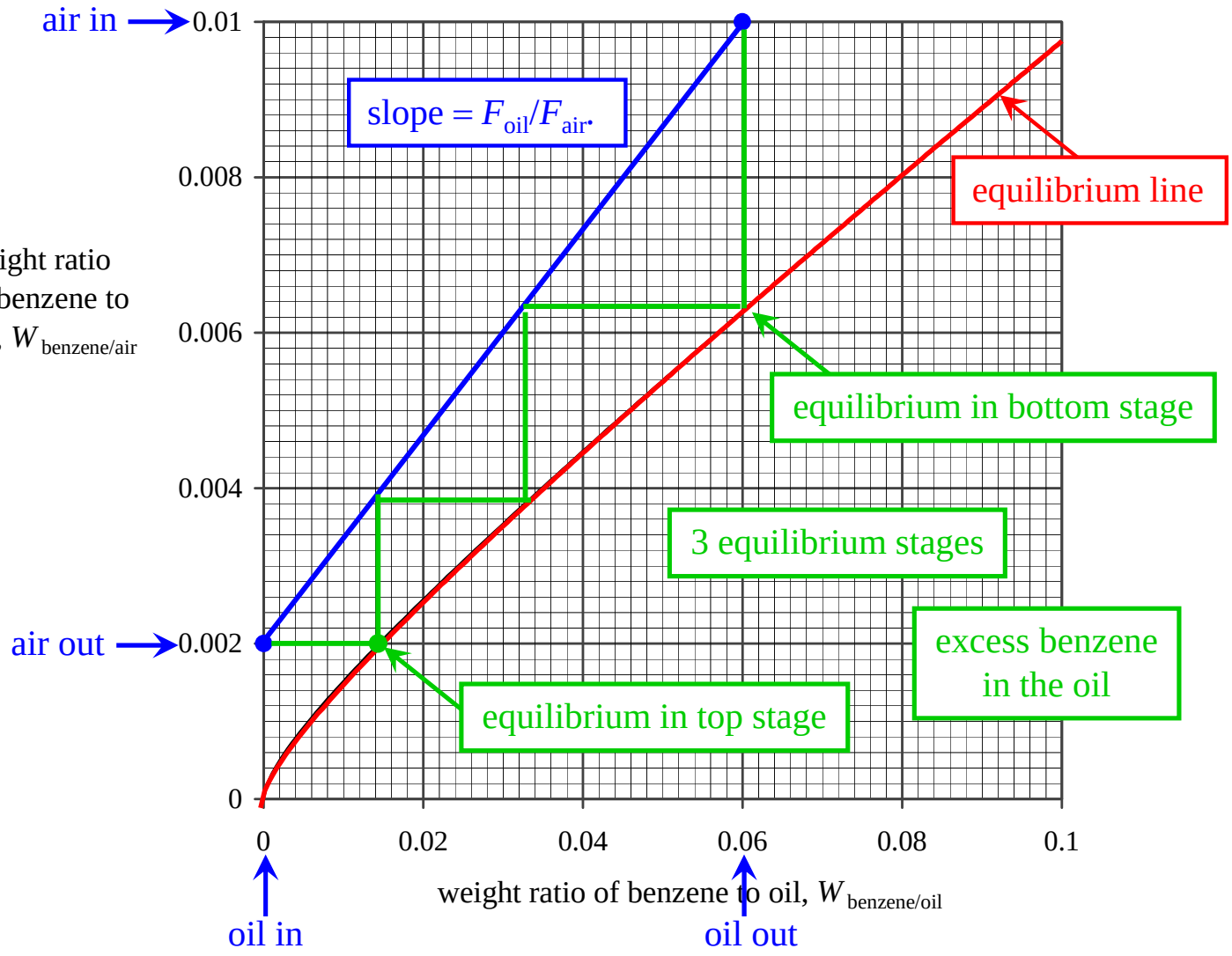
Process looks like Multi-Stage Counter-Current Absorbers.

Need a map like the map we used for Multi-Stage Counter-Current Absorbers.

Graphical Analysis of Multi-Stage Counter-Current Absorbers: Example 1

All compositions given. Calculate F_{oil}/F_{air} and number of stages.



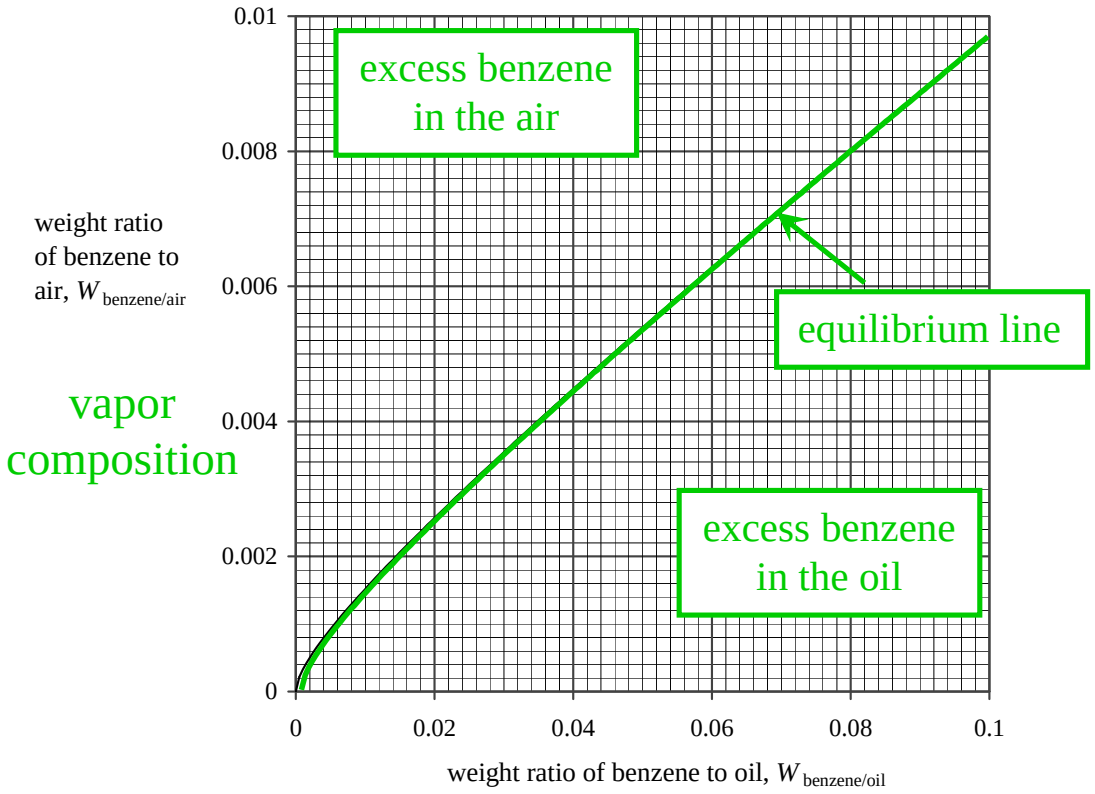


All adjacent (x, y) pairs lie on a line with slope F_{oil}/F_{air}.

This line is the ***Operating Line***.

All (x,y) pairs leaving an equilibrium stage lie on the equilibrium line.

Compare the map for absorber analysis to the T-(x,y) map for flash drums

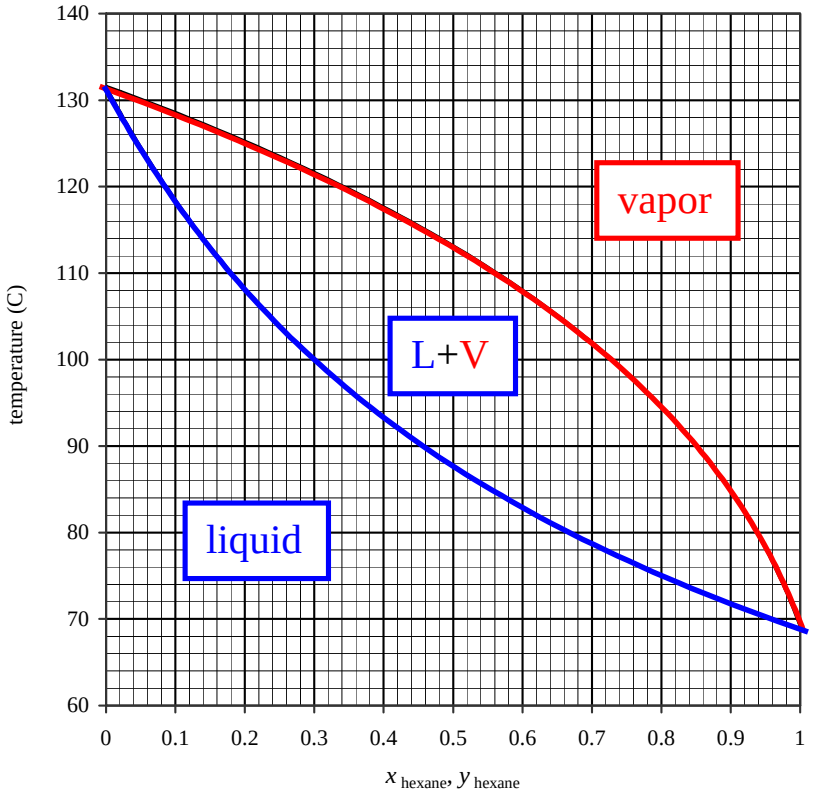


liquid composition

Two phases (L+V) everywhere.

Equilibrium on equilibrium line only.

Need two streams to plot a point:
liquid = x coordinate and vapor = y coordinate.



liquid composition and vapor composition

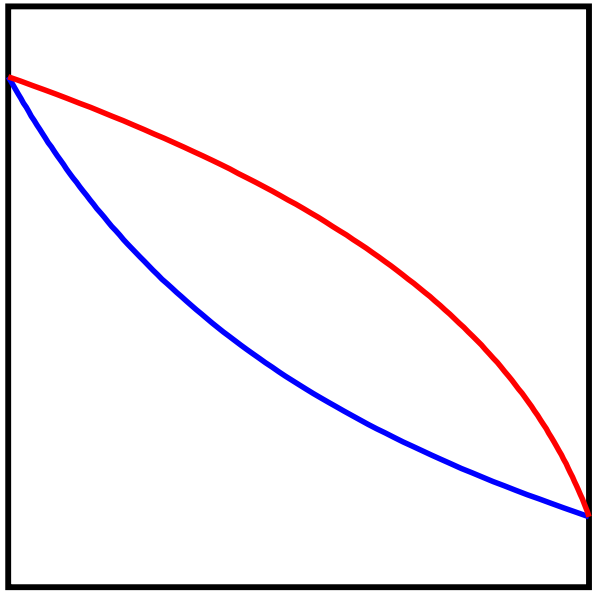
Two phases in L+V region only.

Equilibrium everywhere.

One stream defines a point:
composition = x coordinate and T = y coordinate.

What is the distillation analog of the map for absorber analysis?

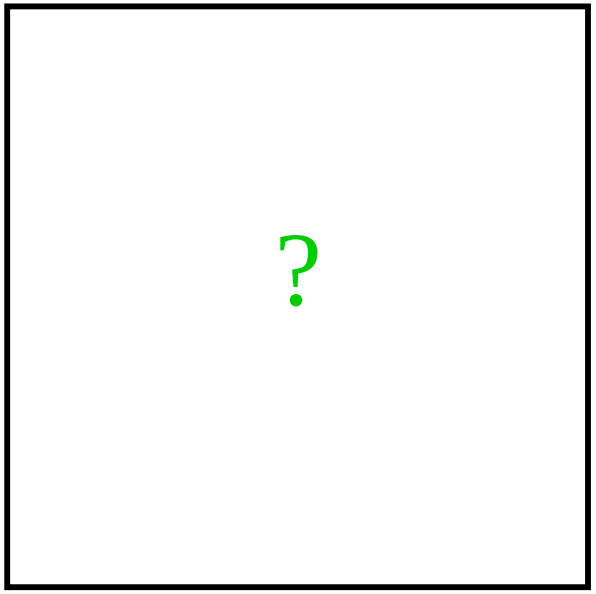
temperature



$x_{benzene}$, $y_{benzene}$

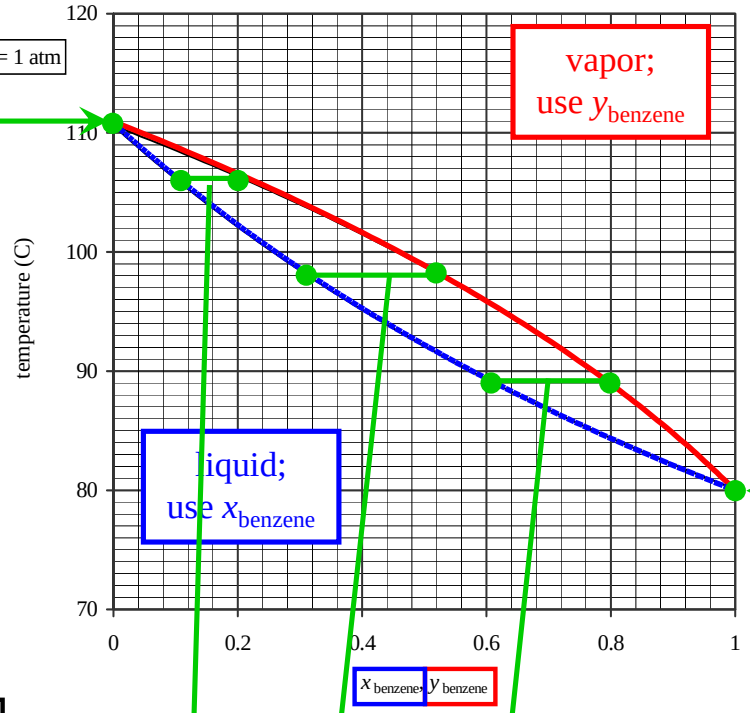
replot data from L+V region

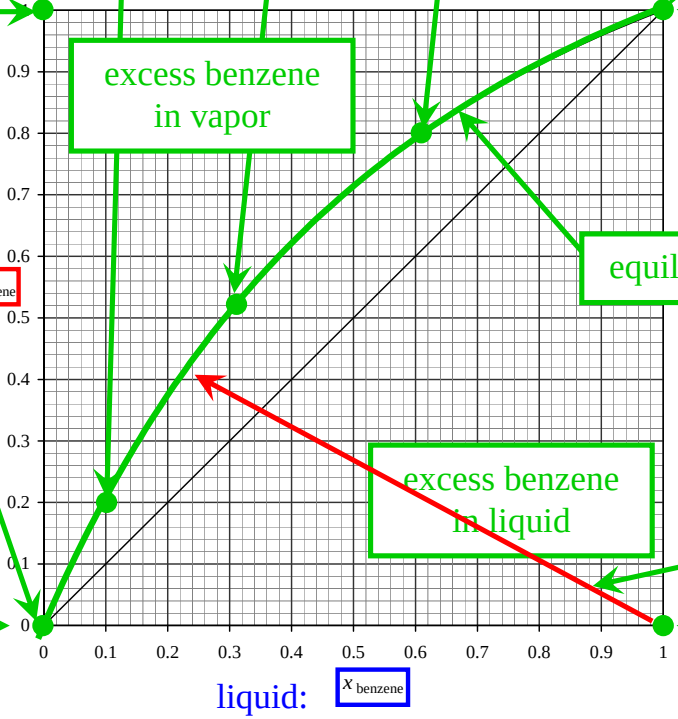
$y_{benzene}$



$x_{benzene}$

Mapping from a *T*-(*x*,*y*) Phase Map to a *x*-*y* Phase Map





pure toluene:
$x_{benzene} = 0$, $y_{benzene} = 0$

pure benzene:
$x_{benzene} = 1$, $y_{benzene} = 1$

B
T

B
B

T
T

T
B

tie line at 89°C:
$x_{benzene} = 0.62$, $y_{benzene} = 0.80$

tie line at 98°C:
$x_{benzene} = 0.31$, $y_{benzene} = 0.52$

tie line at 106°C:
$x_{benzene} = 0.10$, $y_{benzene} = 0.20$

Equilibrium everywhere;
L+V in one region only.

One stream is a point:
(x_B, T) or (y_B, T)

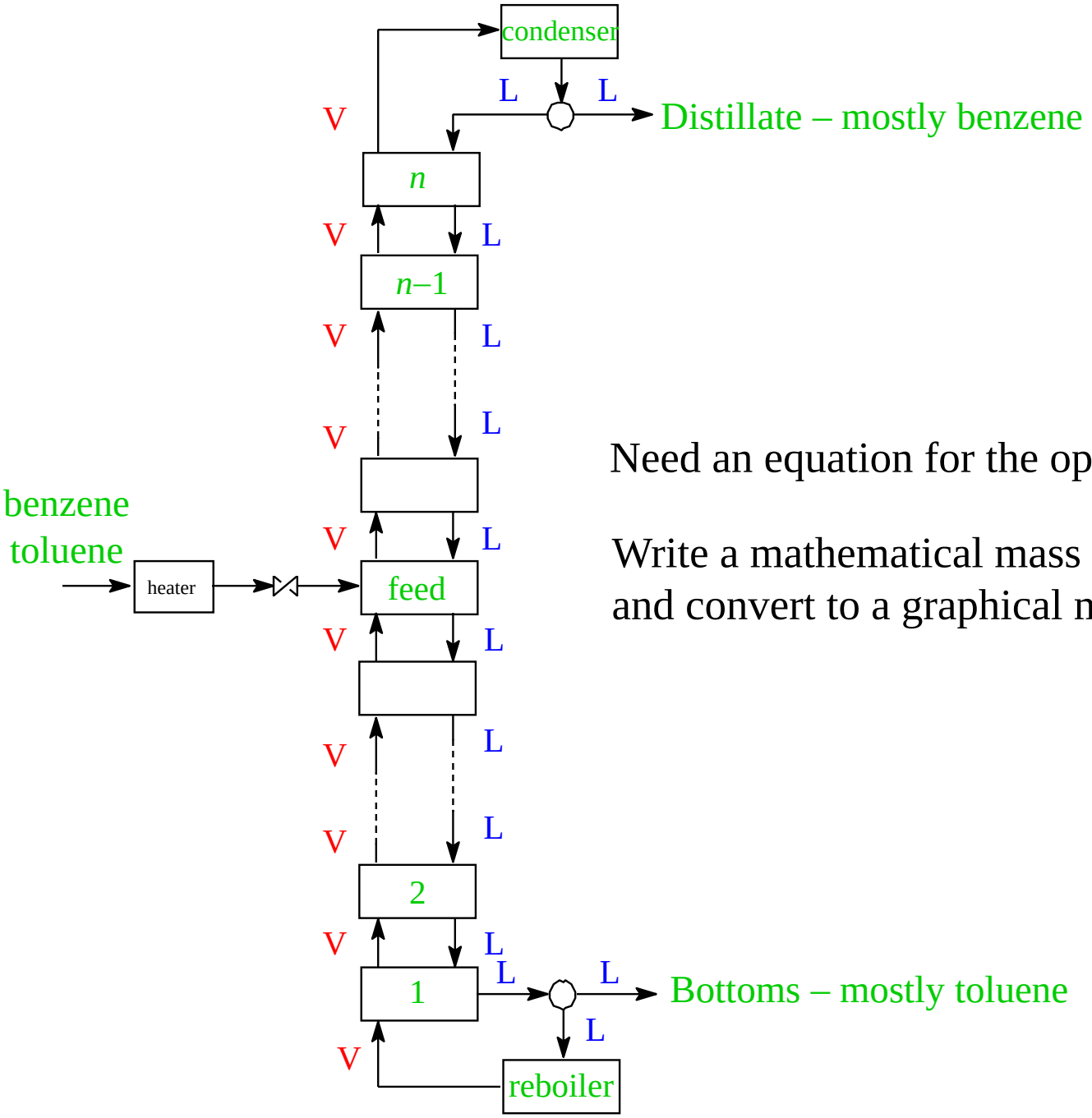
Use tie lines.

L+V everywhere;
equilibrium on one line only.

Need two streams for a point:
(x_B, y_B)

Use trajectory paths or operating lines.

A Distillation Column



Need an equation for the operating line.

Write a mathematical mass balance and convert to a graphical model.

Distillation Column: Mass balance on Consecutive Equilibrium Stages. pp. 284-5

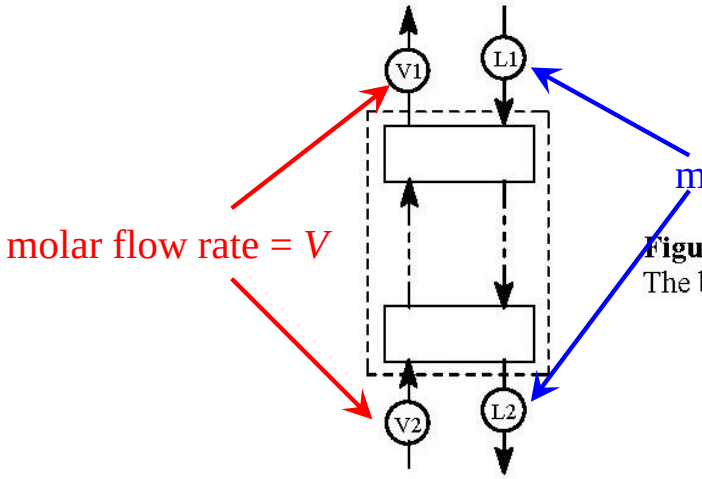


Figure 4.80. System borders around two or more stages in a distillation column. The borders must not include the feed stage.

Assume steady state and no chemical reaction. Thus a mass balance on benzene (B) translates to a mol balance on B. Define F as flow rate in mol/min.

$$\text{molar flow rate of B in} = \text{molar flow rate of B out} \tag{4.36}$$

$$F_{B,V2} + F_{B,L1} = F_{B,V1} + F_{B,L2} \tag{4.37}$$

$$F_{B,V2} - F_{B,V1} = F_{B,L2} - F_{B,L1} \tag{4.38}$$

Define V as the total molar flow rate of a vapor stream, in mol/min. Define L as the total molar flow rate of a liquid stream, in mol/min. A combined overall balance on energy and mass requires $V_{in} = V_{out}$ and $L_{in} = L_{out}$. Set the total molar flow rates of both streams V1 and V2 equal to V. Set the total molar flow rates of both streams L1 and L2 equal to L.

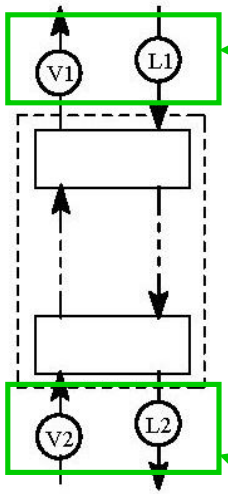
$$F_{total,V1} = F_{total,V2} = V \tag{4.39}$$

$$F_{total,L1} = F_{total,L2} = L \tag{4.40}$$

Recall y_B is the mol fraction of B in the vapor and x_B is the mol fraction of B in the liquid. Express the molar flow rate of B in each stream in terms of the total molar flow rate and the mol fraction of B.

$$F_{B,V1} = y_{B,V1}V, \quad F_{B,V2} = y_{B,V2}V, \quad F_{B,L1} = x_{B,L1}L, \quad F_{B,L2} = x_{B,L2}L \tag{4.41}$$

Distillation Column: Mass balance on Consecutive Equilibrium Stages. pp. 284-5



Adjacent liquid-vapor streams: a plotting pair.

Figure 4.80. System borders around two or more stages in a distillation column. The borders must not include the feed stage.

Adjacent liquid-vapor streams: a plotting pair.

Substitute the four relations above into the mass balance, equation 4.38.

$$y_{B,V2}V - y_{B,V1}V = x_{B,L2}L - x_{B,L1}L \qquad (4.42)$$

$$(y_{B,V2} - y_{B,V1})V = (x_{B,L2} - x_{B,L1})L \qquad (4.43)$$

$$\frac{L}{V} = \frac{y_{B,V2} - y_{B,V1}}{x_{B,L2} - x_{B,L1}} = \frac{\text{rise}}{\text{run}} \qquad (4.44)$$

Equation 4.45 obtains for any collection of consecutive equilibrium stages in the stripping section or the rectifying section. Therefore all adjacent liquid+vapor pairs between stages lie on a line of slope L/V on a map of y_B vs. x_B.

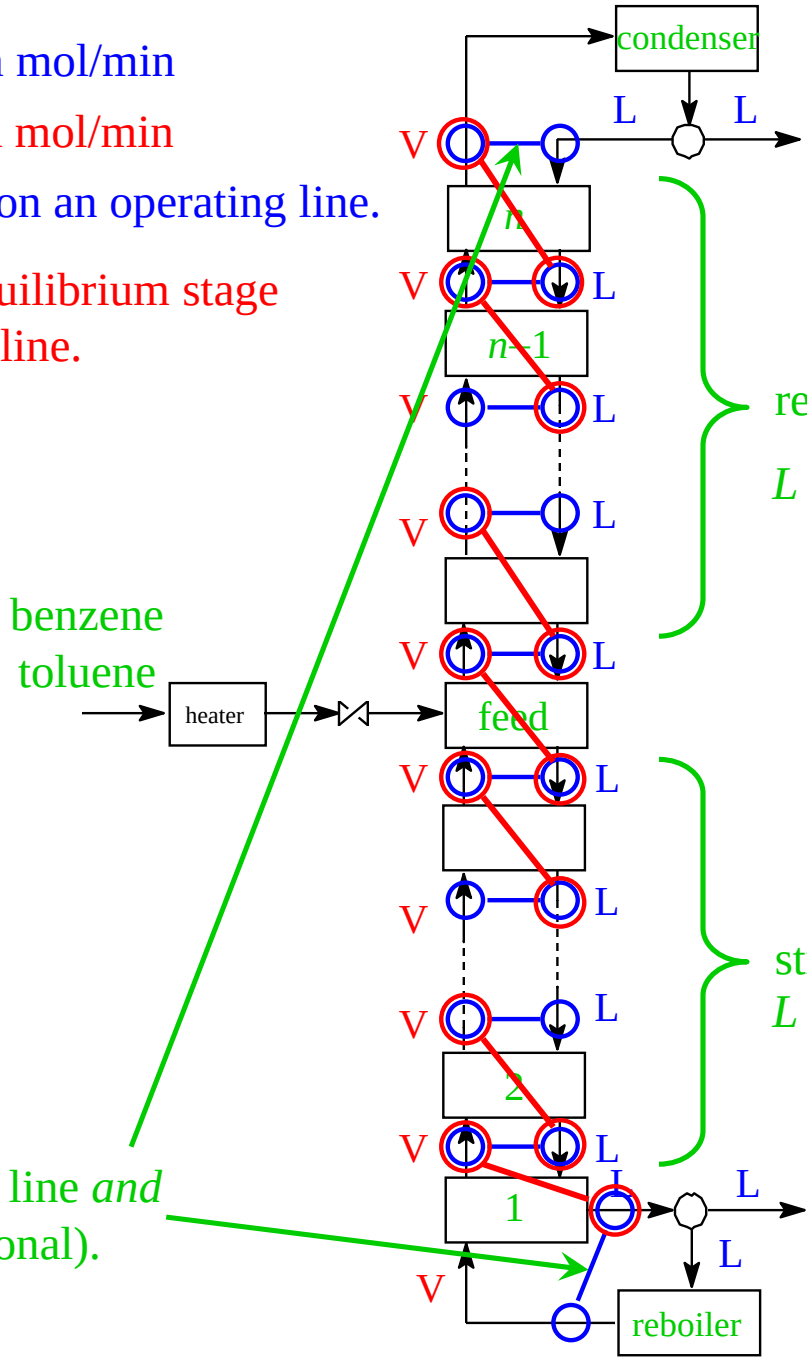
A Distillation Column

$L \equiv$ liquid flow rate, in mol/min

$V \equiv$ vapor flow rate, in mol/min

Adjacent *x*-*y* pairs are on an operating line.

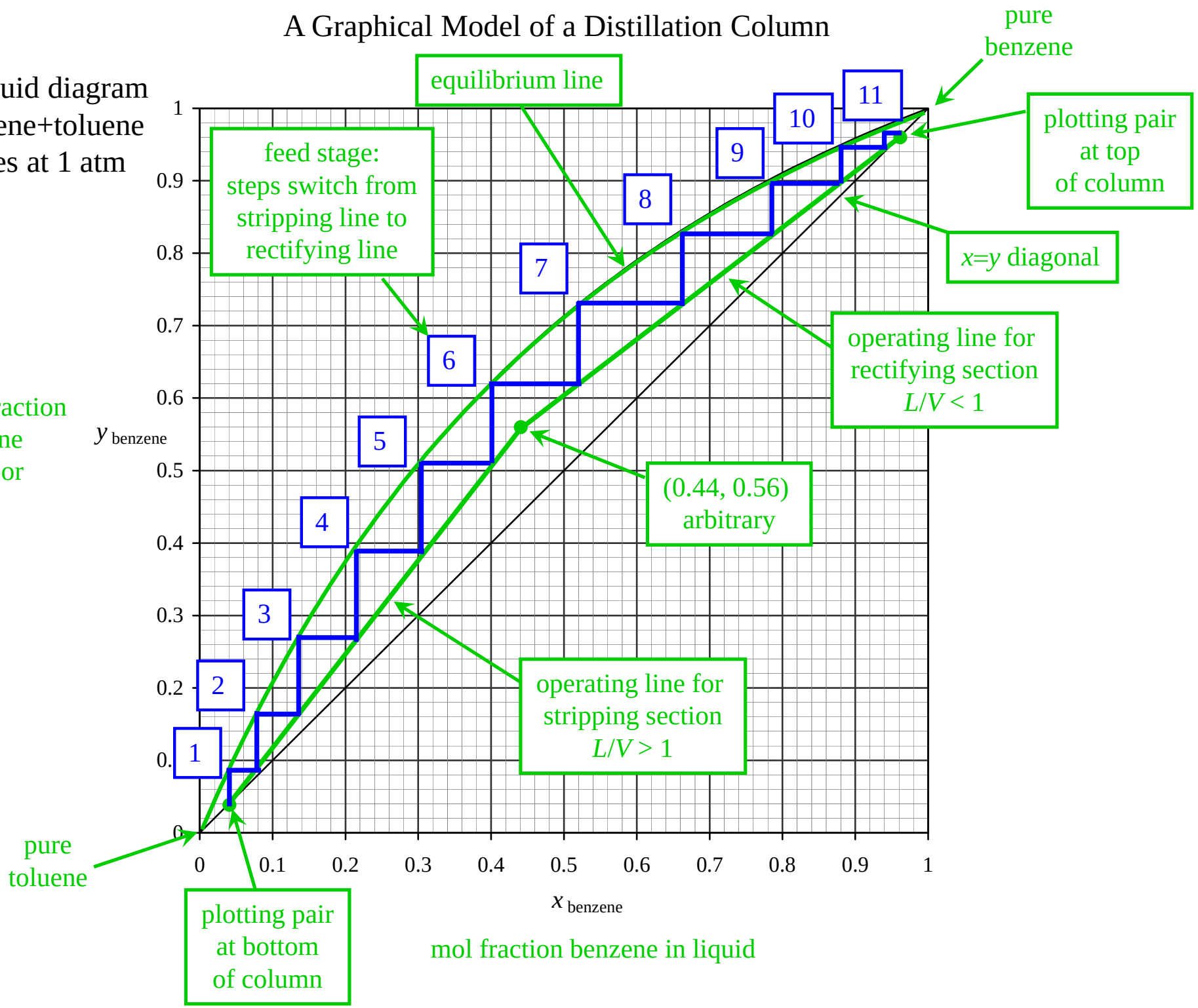
x-*y* pairs leaving an equilibrium stage are on the equilibrium line.



x-*y* pair on operating line *and* on *x*=*y* line (the diagonal).

A Graphical Model of a Distillation Column

vapor-liquid diagram for benzene+toluene mixtures at 1 atm



A Graphical Model of a Distillation Column: Minimum Stages? Minimum Reflux?

Minimum stages?

Minimum reflux?

⇒ max L/V for stripping section,

⇒ min L/V for rectifying section.