CE407 SEPARATIONS

Lecture 09

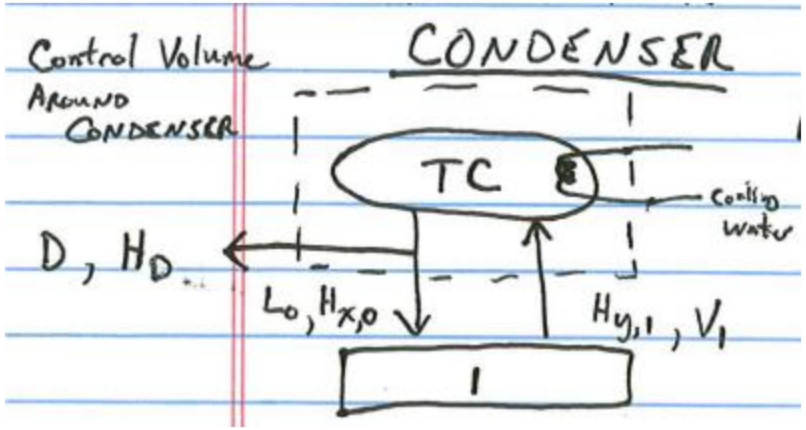
Instructor: David Courtemanche

University at Buffalo
Department of Chemical and Biological Engineering
School of Engineering and Applied Sciences

Continuous Distillation – Enthalpy Balances

McSH pp 694-701, pp 679, 682 eq 21.1 and 21.2

- How much energy does one need to remove via condenser and add via reboiler?
- ## Condenser
- Control Volume around condenser



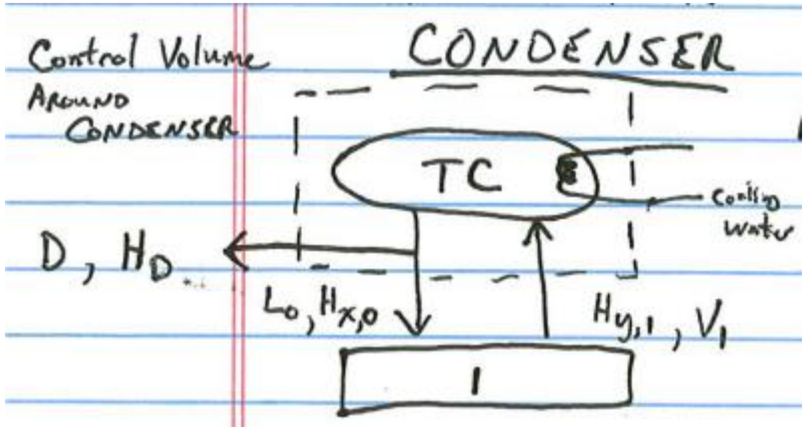
- Heat added = Enthalpy out – enthalpy in

$$-q_c = DH_D + L_0 H_{x,0} - V_1 H_{y,1}$$
$$= (D + L_0) H_{x,0} - V_1 H_{y,1}$$

- Note: $\mathbf{q_c}$ is defined as the amount of heat **REMOVED** via the condenser and is a positive number. The enthalpy balance is the amount of heat added, therefore the term appears as $\mathbf{-q_c}$ in the equation. The fact that $\mathbf{-q_c}$ is therefore a negative term is consistent with the fact that we are removing heat to affect a phase change from vapor to liquid

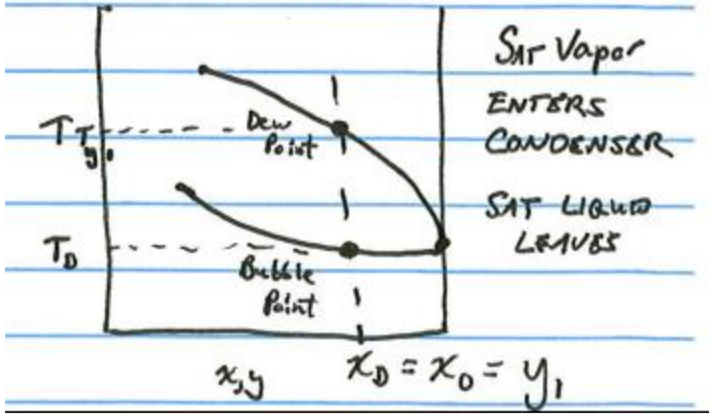
Enthalpy Balances: Condenser, continued

- $-q_c = (D + L_0)H_{x,0} - V_1 H_{y,1}$
- But from mass balance we know that $V_1 = D + L_0$
- $-q_c = (D + L_0)H_{x,0} - (D + L_0)H_{y,1}$
- And from definition of reflux ratio $\mathbf{L_0 = D\,R}$



$$\boxed{-q_c = D(1 + R)\left(H_{x,0} - H_{y,1}\right)}$$

- It's not as simple as just looking at Heats of Vaporization
- You have the temperature changing from Dew Point to Bubble Point
- Heats of Vaporization are defined for a pure material at a given temperature (usually the normal boiling temperature for pure material) and we are condensing over a range of temperatures



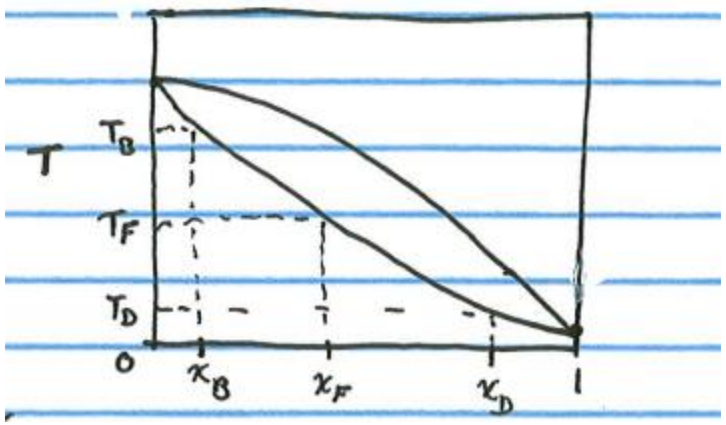
Enthalpy Balances: Reboiler

- Set up Control Volume around entire column

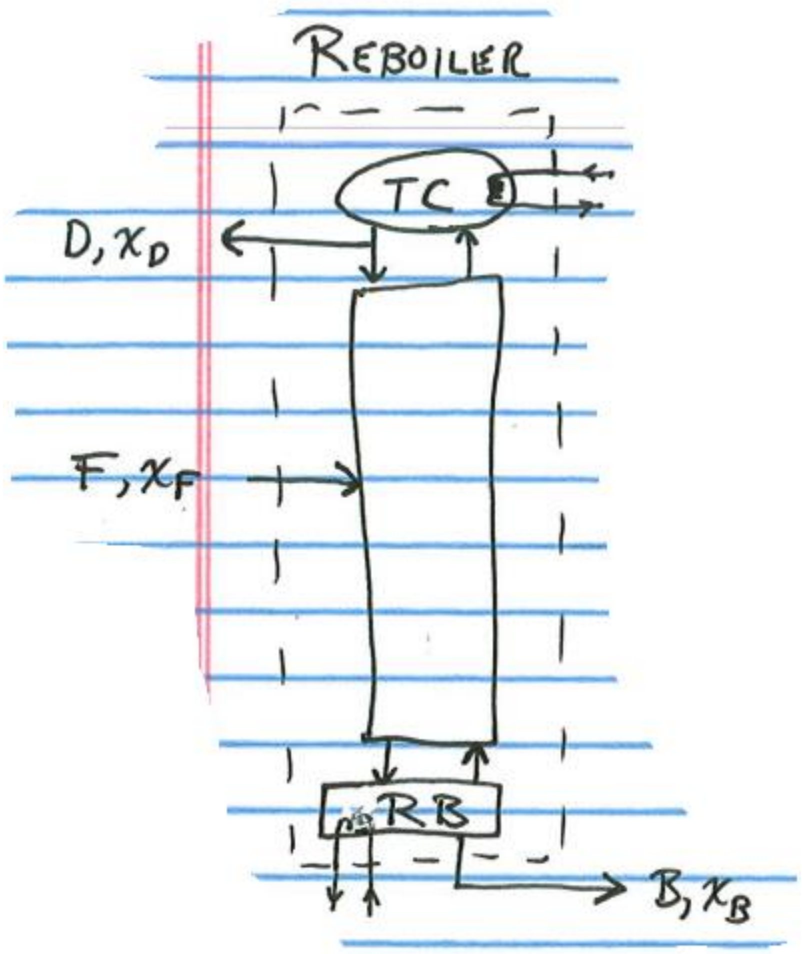
Heat added = Enthalpy out – enthalpy in

$$\boxed{q_r - q_c = DH_D + BH_B - FH_F}$$

- q_r is defined as heat ADDED via the Reboiler and is a positive number
- We will need to determine the temperature of each stream in order to calculate enthalpies



Txy diagram for saturated liquid feed case



Enthalpy Balances

- We have the temperature and composition of all streams
  - Calculate enthalpy of each stream
  - Start with enthalpy balance around condenser
    - Solve for q_c
  - Next evaluate enthalpy balance around entire column
    - Solve for q_r

Enthalpy Balances – Heat Loads

Condenser

- Use q_c to determine rate of cooling water required for condenser

$$\boxed{q_c = \dot{m}_{cw} C^L_{p\,H_2O}(T_{out} - T_{in})}$$

- Where $\dot{m}_{cw}$ is mass flow rate of cooling water
- $C^L_{p\,H_2O}$ is the heat capacity of liquid water
  - Typically $C^L_{p\,H_2O} \approx 1\ \frac{cal}{g\ °\mathrm{C}}$
- T_{in} is the incoming temperature of the cooling water
- T_{out} is the outgoing temperature of the cooling water
  - this may be limited by thermal pollution concerns
  - of course, you don’t want this stream to reach a boiling temperature

Enthalpy Balances – Heat Loads

Reboiler

- Use q_r to determine rate of steam consumption required for reboiler

$$\boxed{q_r = \dot{m}_{steam}\,\Delta H_{H_2O}^{vap}}$$

- Where $\dot{m}_{steam}$ is mass flow rate of steam
- $\Delta H_{H_2O}^{vap}$ is the heat of the steam phase change

- This equation assumes steam enters as saturated vapor and exits as saturated steam – consult steam tables for enthalpy change of steam that has varying quality values

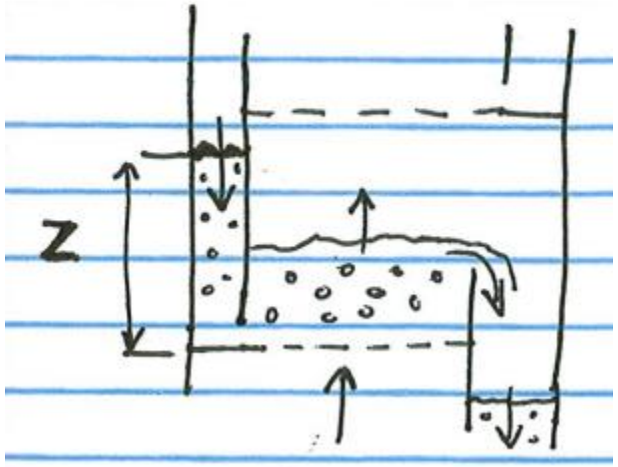
	T (°C)	$P_{H_2O}^{sat}(kPa)$	$\Delta H_{H_2O}^{vap}\left(\frac{kJ}{kg}\right)$
	100	101.3	2257
~150 # steam	188	1200	1986

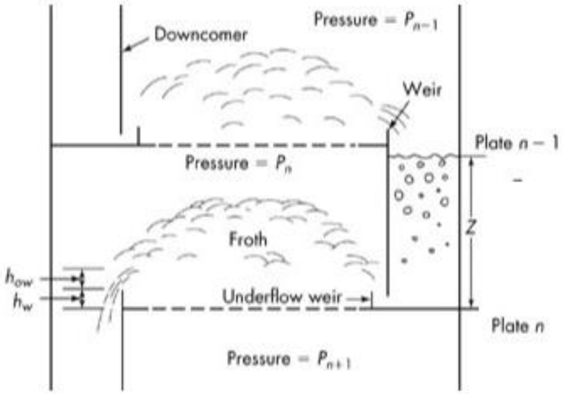
Continuous Distillation – Tower Design

McSH pp 701-712

Design of Sieve Plate Trays

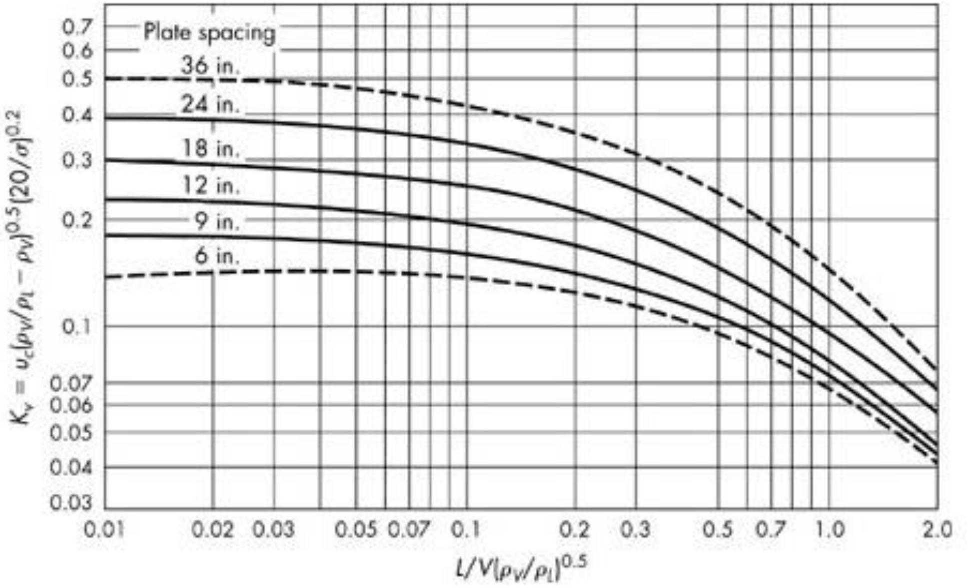
- Pressure increases as you progress down the tower
- The pressure is needed to motivate the vapor through the holes in the tray and through the liquid held up on the tray
- Due to the ΔP, a column of liquid is held up in the downcomer (similar to a monometer) of height **Z**
- The text discusses methods for calculating **Z**, but we won't touch on it at this point
- The important point is that if **Z** exceeds the distance to the weir on the plate immediately above then the column experiences **FLOODING** and the plates won't function properly
- The diameter of the column must be specified such that the vapor velocity does not exceed the **"Flooding Velocity"**





Flooding

- Figure 21.26 in McSH: Note that this is a log-log graph!
- Choose curve corresponding to your tray spacing
- Calculate $\frac{L_{mass}}{V_{mass}}\sqrt{\rho_V/\rho_L}$
  - Note that **L** and **V** are MASS flow rates
  - Note that $\boldsymbol{\rho_V}$ and $\boldsymbol{\rho_L}$ are MASS densities
  - **L/V** we have used in the past were molar flows
- Find $\boldsymbol{K_V}$ from chart
- Use equation 21.68 to calculate flooding velocity

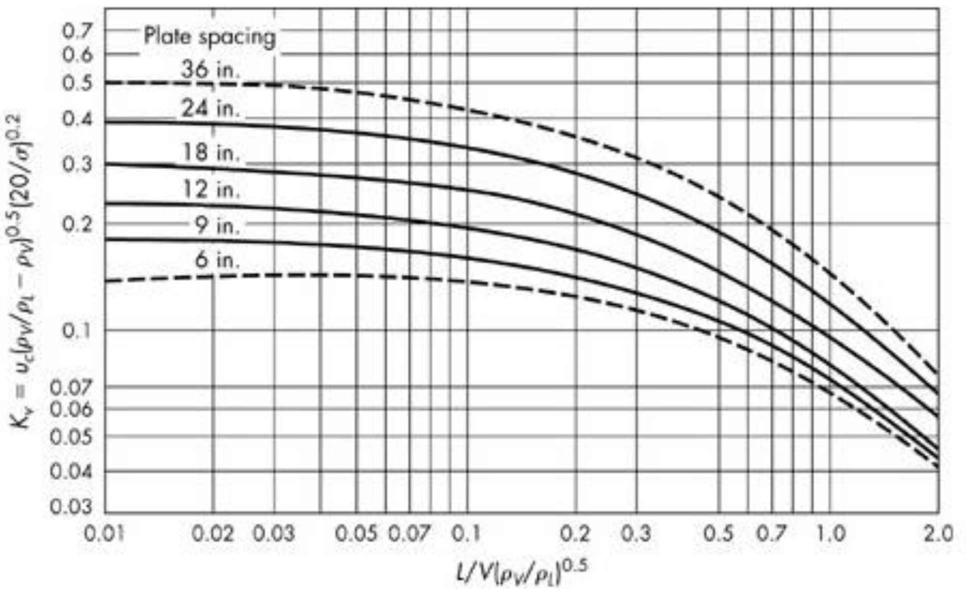


$$u_c = u_{flooding} = K_V\sqrt{\frac{\rho_L - \rho_V}{\rho_V}}\left(\frac{\sigma}{20}\right)^{0.2}$$

- σ is the surface tension in dyn/cm, **u** is in ft/s on this graph
- A given chart will correspond to **u** in ft/s or m/s: *be sure you know which it is!*

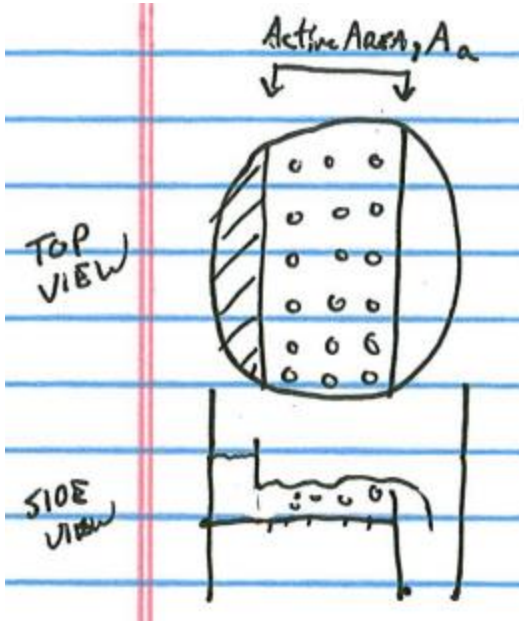
Flooding

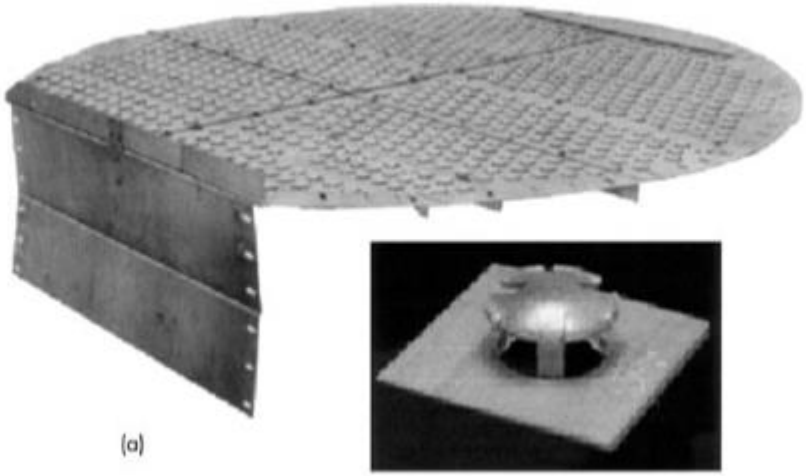
- Calculate $\frac{L_{mass}}{V_{mass}}\sqrt{\rho_V/\rho_L}$
  - Note that **L** and **V** are MASS flow rates
  - Note that $\boldsymbol{\rho_V}$ and $\boldsymbol{\rho_L}$ are MASS flow densities
  - **L/V** we have used in the past were molar flows
  - $\frac{L_{mass}}{V_{mass}} = \frac{L\,\overline{MW_L}}{V\,\overline{MW_V}}$
  - When we are evaluating at the top of the tower the flows are often close to pure light component and $\overline{MW_L} \approx \overline{MW_V}$
  - Therefore $\frac{L_{mass}}{V_{mass}} \approx \frac{L}{V}$
  - $\frac{L}{V} = \frac{R}{R+1}$ can be used for $\frac{L_{mass}}{V_{mass}}$ as long as we are aware that it only applies when $\overline{MW_L} \approx \overline{MW_V}$



Flooding, Continued

- Now we have a value for the a vapor velocity that will cause flooding.
- We will add a safety factor because we don't want to operate on the edge of flooding conditions
    - Various sources use different factors, let's choose $u \approx 0.7u_{flood}$
- Most of the plate is covered by holes
- $\boldsymbol{A = Total\ Area = \frac{\pi D^2}{4}}$
- Downcomer, etc cover 15% of total area
- Net area for flow = **0.85A**





(a)

(b)

Flooding, Continued

$$V = u\,A_n \frac{P}{RT}$$

Molar vapor flow = (volumetric flow) * (moles/volume)

- From ideal gas law PV = nRT you get $\frac{P}{RT} = \frac{n}{V} = \frac{moles}{Volume}$
- In this context V is just a volume

- $A_n = 0.85\frac{\pi D^2}{4}$ net area for flow
- Steps
  - Calculate u_{flood} and apply safety factor
  - Use molar flow rate V to calculate A_n
  - Calculate required column diameter

- **Note: Column is most susceptible to flooding at the top of the tower. Use conditions corresponding to the top of the tower in this evaluation!**

Flooding Example

- We have a distillate flow rate of 3259 mol/minute of CCL_4 (light) and C_8H_{18} (heavy)
  - $x_D = 0.859$
- Reflux ratio = 2.55, Tray Spacing = 24"
- Flooding velocity is calculated at TOP of tower
- Problem Statement indicates that we should assume denisites of the liquid and vapor to be that of pure CCL_4
  - Liquid density: $\rho_L = 1490\ \frac{kg}{m^3}$
- Vapor density: By the Ideal Gas Law we can calculate molar volume
- $$V = \frac{RT}{P} = \frac{83.14 \frac{bar\ cm^3}{mol\ K}(273.15+76.75)\ k}{1.013\ bar} = 2.872 * \ 10^4 \frac{cm^3}{mol}$$
  - Then the mass density can be calculated as
  - $$\rho_V = \frac{1\ mol}{2.872 * 10^4\ cm^3} * \frac{153.823\ g}{mol} * \frac{kg}{1000\ g} * \frac{10^6 cm^3}{m^3} = 5.34\ \frac{kg}{m^3}$$
    - MW CCl_4 = 153.823

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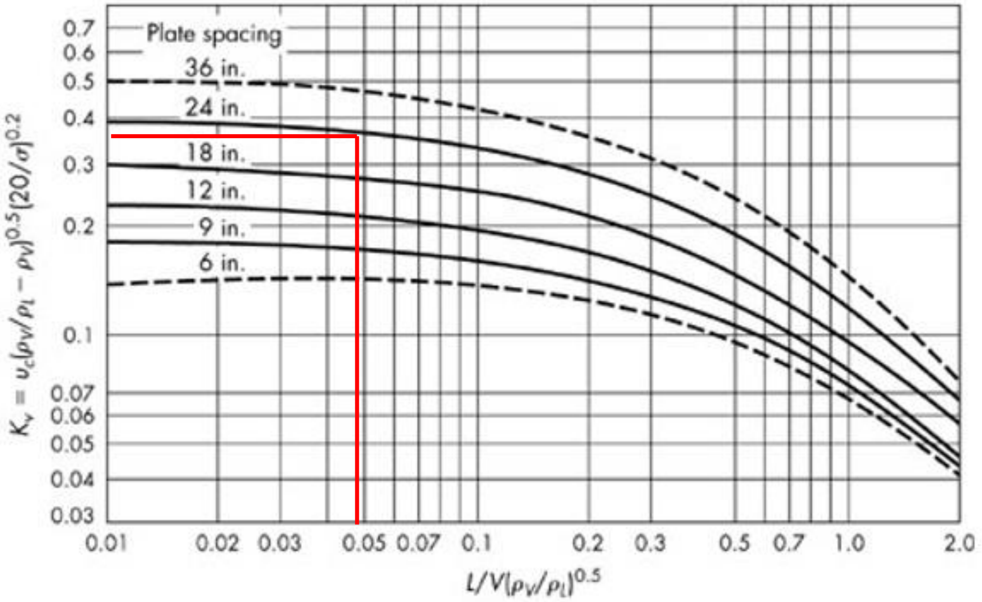
Flooding Example

- Near the top of the tower (where the mole fractions are near 1.0), the average molecular weight of the liquid and the vapor are approximately equal at any location
  - At the top of the tower $\frac{L_{mass}}{V_{mass}} = \frac{L * MW_L}{V * MW_V} \approx \frac{L}{V} = \frac{R}{R+1} = \frac{2.55}{2.55+1} = \mathbf{0.718}$

- $\frac{L_{mass}}{V_{mass}}\sqrt{\frac{\rho_V}{\rho_L}} = \mathbf{0.718}\sqrt{\frac{5.34\,\frac{kg}{m^3}}{1490\,\frac{kg}{m^3}}} = \mathbf{0.043}$

- $K_V = u_c\sqrt{\frac{\rho_V}{\rho_L - \rho_V}}\left(\frac{20}{\sigma}\right)^{0.2} = 0.37$

- Unless your surface tension is very different from water, the surface tension factor can be ignored



- $u_c = u_{flooding} = K_V\sqrt{\frac{\rho_L - \rho_V}{\rho_V}} = 0.37\sqrt{\frac{1490 - 5.34}{5.34}} = 6.17\,\frac{ft}{s}$

Flooding Example

- Vapor volumetric flow rate:
- V molar flow rate $V = L + D = (R+1)D = 3.55 * \ 3259\ \frac{mol}{min} = 11{,}569\ \frac{mol}{min}$
- Molar density $\rho_V = \frac{P}{RT} = \frac{1.013\ bar}{83.14 \frac{bar\ cm^3}{mol\ K}(273.15+76.75)\ k} = 3.482 * \ 10^{-5} \frac{mol}{cm^3} * \frac{10^6\ cm^3}{m^3} = 34.82 \frac{mol}{m^3}$
- $Q = \frac{V}{\rho_V} = \frac{11{,}569 \frac{mol}{min}}{34.82 \frac{mol}{m^3}} = 332.2\ \frac{m^3}{min} * \frac{min}{60\ s} = 5.54\ \frac{m^3}{s} * \left(\frac{ft}{0.305\ m}\right)^3 = 195.3\ \frac{ft^3}{s}$

Flooding Example

- **Column diameter:**
- $Q = A_n * u = 0.85\frac{\pi D^2}{4} * u$
  - (Volumetric flow rate = Area * velocity)
- Column is to operate at 50% of flooding velocity:
- $u = 0.5 * u_{flooding} = 0.5 * 6.17\frac{ft}{s} = 3.09\frac{ft}{s}$
- $Q = 195.3\frac{ft^3}{s} = 0.85\frac{\pi D^2}{4} * 3.09\frac{ft}{s} = 2.06\frac{ft}{s} * D^2$
- $D^2 = \frac{195.3\frac{ft^3}{s}}{2.06\frac{ft}{s}} = 94.67\, ft^2$
- $\boldsymbol{D = 9.7\, ft}$