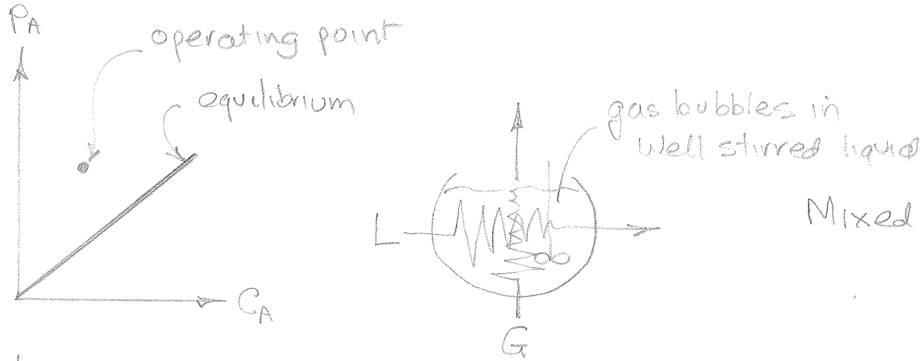
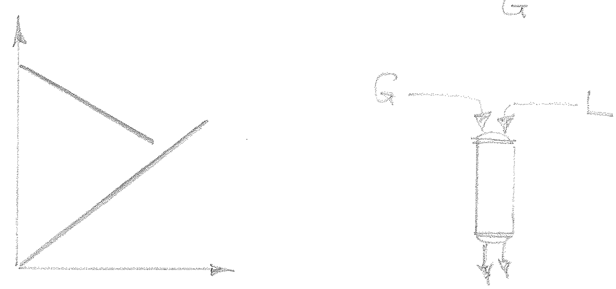
24.1

(a)



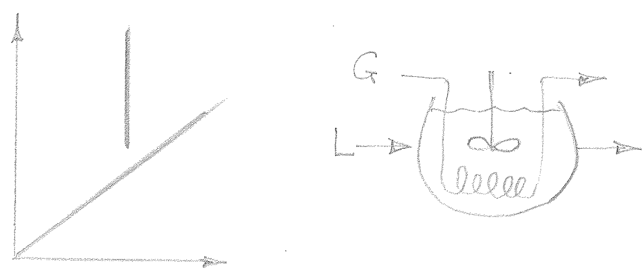
Mixed-mixed

(b)



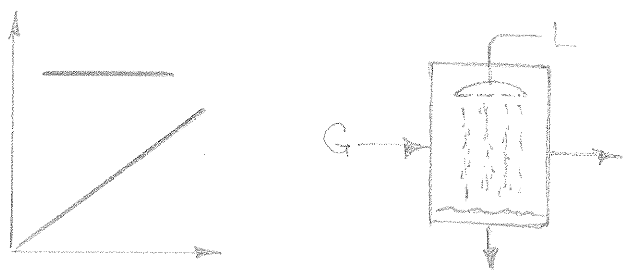
Cocurrent
plug flow

(c)



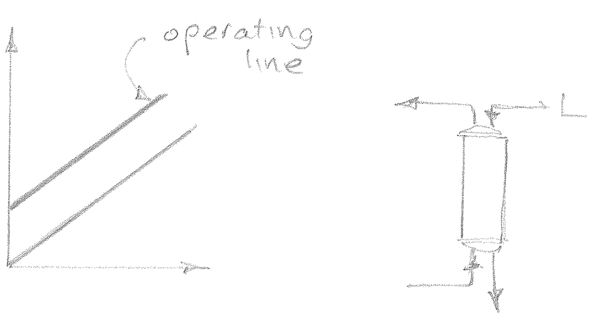
Plug-gas
mixed-liquid

(d)



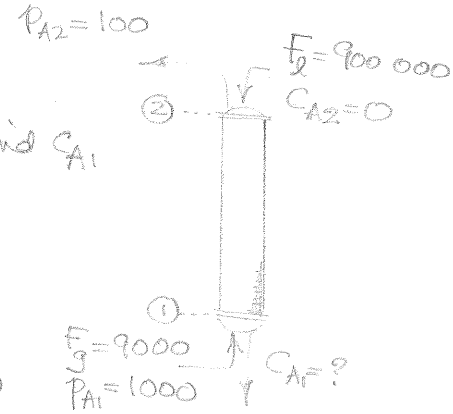
Mixed-gas
plug-liquid

(e)



Countercurrent
plug flow

24.3 Straight mass transfer — Counter current — $H_A = 18$



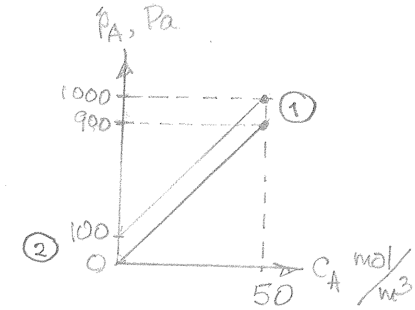
By material balance between ① & ② we find C_{A1}

$$\frac{90000}{10^5}(1000-100) = \frac{900\,000}{55\,556}(C_{A1}-0)$$

or $C_{A1} = 50$ mol/m³

At equilibrium $p_A^* = H_A C_A$ ... or $\overset{\text{at } C_{A1}}{p_{A1}^*} = 18 \times 50 = 900$

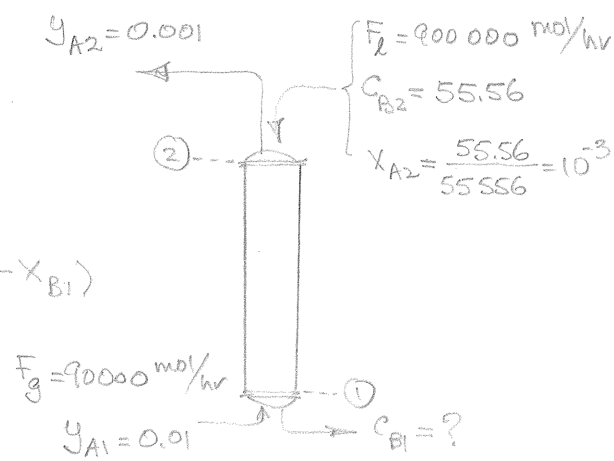
Now draw the p_A vs C_A diagram. We see that the operating & equilibrium lines are parallel. Thus the rate of transfer is the same everywhere. So we find



$$-r_A'''' = \frac{1}{\frac{1}{k_{Ag}a} + \frac{H_A}{k_{Al}a}}(p_A - p_A^*) = \frac{1}{\frac{1}{0.36} + \frac{18}{72}}(1000-900) = 33$$

$$\therefore V_r = \frac{F_g}{\pi}\int_{1000}^{100} \frac{dp_A}{-r_A''''} = \frac{90\,000}{10^5}\,\frac{(1000-100)}{33} = 24.5 \text{ m}^3$$

24.5 By material balance find C_{B1} (see diagram on right)



$$F_g(Y_{A1} - Y_{A2}) = F_l(X_{A2} - X_{A1})$$

or

$$90000\left(\frac{0.01}{0.99} - \frac{0.001}{0.999}\right) = 900\,000\,(0.001 - X_{B1})$$

or $C_{B1} = 5$ mol/m³

We need to evaluate E_i & M_H to find the rate

$$E_i = 1 + \frac{\mathcal{D}_B C_B}{b\,\mathcal{D}_A C_A} = 1 + \frac{C_B}{C_A} = 1 + \frac{C_B H_A}{p_{Ai}} = 1 + \frac{10^5 C_B}{p_{Ai}}$$

$$M_H = \sqrt{\frac{\mathcal{D}_A k C_B}{k_{Al}^2}} = \infty$$

Since $E_i \ll M_H$ Fig 23.4 shows that $E = E_i$

24.5 continued

Now determine the rate at top, bottom and intermediate point

At top, ②

$$E_i = 1 + \frac{55.56 \times 10^5}{100} = 5.556 \times 10^4$$

here I am guessing that all the resistance is in the gas film, so I put $p_{A2}^* = p_{A2}$

Because $E_i \ll M_H$ we say that $E = E_i = 5.556 \times 10^4$. Now to the rate

$$-r_A'''' = \frac{1}{\frac{1}{k_{Ag}a} + \frac{H_A}{k_{Al}aE} + \frac{H_A}{k C_B f_l}} \cdot p_A = \frac{1}{\underbrace{\frac{1}{0.36}}_{<99\%} + \underbrace{\frac{10^5}{72(5.556 \times 10^4)}}_{<1\%\text{ of resistance}} + \frac{10^5}{\infty}} \cdot p_A = 0.36\, p_A$$

At bottom, ①

$$E_i = 1 + \frac{55.56 \times 10^5}{100} = 501$$

I am again guessing that all resistance is in the gas film

so

$$-r_A'''' = \frac{1}{\frac{1}{0.36} + \frac{10^5}{72(501)} + 0} \cdot p_A = \frac{1}{\frac{1}{0.36} + \frac{1}{0.36}} \cdot p_A = 501$$

this shows that 50% of resistance is in the liquid film. This is not what we guessed

Try again

Guess $p_{Ai} = 500$, repeat the procedure. We find $E_i = 1001$ and from the rate 1/3 of the resistance is in the gas film. Wrong guess

Try once again

Guess $p_{Ai} = 100$, or 10% resistance in the gas film. Then $E_i = 5001$ &

$$-r_A'''' = \frac{1}{1/0.36 + 1/3.6} p_A = 0.33\, p_A$$

91% of resistance in gas film — close enough.

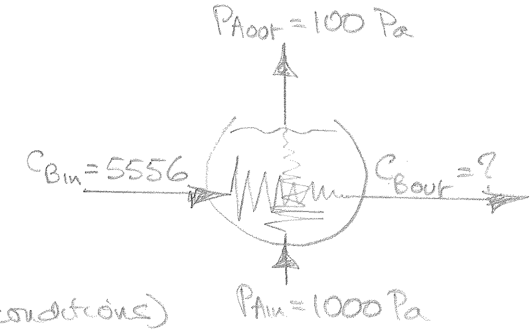
So $(-r_A'''')_{mean} = \frac{0.36 + 0.33}{2} = 0.345\, p_A$

Hence

$$V = \frac{F_g}{\pi} \int \frac{dp_A}{-r_{A,mean}''''} = \frac{90000}{10^5} \int_{10^2}^{10^3} \frac{dp_A}{0.345\, p_A} = \frac{90000}{34500} \ln \frac{10}{1} = 6\ m^3$$

Gas film resistance is 91% of total, 9% is from liquid

24.7 First determine C_{Bout} -- see sketch at right



$$F_g(Y_{out} - Y_{in}) = F_\ell(X_{in} - X_{out})$$

or

$$90000\left(\frac{0.01}{0.99} - \frac{0.001}{0.999}\right) = 9000\left(\frac{5556}{55556} - \frac{C_{Bout}}{55556}\right)$$

$\therefore\ C_{Bout} = 500\ \text{mol}/\text{m}^3$

Next determine the rate (note, at the exit conditions)

$$M_H = \sqrt{\frac{\mathscr{D} k C_B}{k_{A\ell}}} = \sqrt{\frac{3.6\times10^{-6}(2.6\times10^{5})500}{0.72^2}} = 30$$

$$E_i = 1 + \frac{C_B H_A}{p_{Ai}} = 1 + \frac{500(10^5)}{\underset{\text{or lower}}{100}} = 5\times10^5,\ \text{or higher}$$

Since $E_i \gg M_H$, Fig 23.4 shows that $E = M_H = 30$

$$-r_A''' = \frac{1}{\frac{1}{k_{Ag}a} + \frac{H_A}{k_{A\ell}aE} + \frac{H_A}{kC_B f_\ell}} \cdot p_A = \frac{1}{\frac{1}{0.72} + \frac{10^5}{144(30)} + \frac{10^5}{2.6\times10^5(500)(0.9)}} \cdot p_A$$

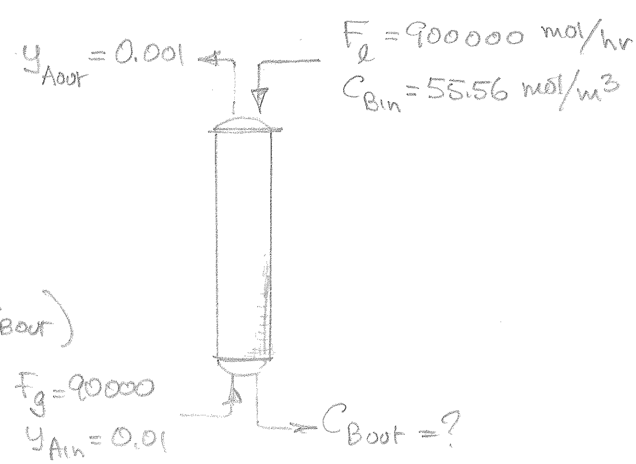
$$= \frac{1}{\underbrace{1.389}_{5.7\%\ \text{of the resistance}} + \underbrace{23.15}_{94\%\ \text{of the resistance}} + 0} = 0.041\ p_A$$

$\therefore$

$$V_r = \frac{F_g}{\pi}\frac{\Delta p_A}{(-r_A''')} = \frac{90000(1000-100)}{10^5(0.041)100} = 197.6\ \text{m}^3$$

Liquid film contributes 94.3% of the resistance

24.9 First determine C_{Bout} by a material balance



$$F_g(Y_{Ain} - Y_{Aout}) = F_\ell(X_{Bout} - X_{Bin})$$

or

$$90000\left(\frac{0.01}{0.99} - \frac{0.001}{0.999}\right) = \frac{900000}{55556}(55.56 - C_{Bout})$$

From which

$$C_B = 5\ \text{mol}/\text{m}^3$$

24.9 continued

At top $M_H = \sqrt{\frac{\mathscr{D} k C_B}{k_{Al}}} = \sqrt{\frac{3.6\times10^{-6}(2.6\times10^7)55.56}{0.72^2}} = 100$

$E_i = 1 + \frac{55.56(10^5)}{100} = 55561 \gg M_H \quad \therefore E = M_H = 100$

$$-r_A'''' = \frac{1}{\frac{1}{k_{Ag}a} + \frac{H_A}{k_{Al}aE} + \frac{H_A}{kC_B f_l}} \cdot p_A = \frac{1}{\frac{1}{0.36} + \frac{10^5}{72(100)} + \frac{10^5}{2.6\times10^7(55.56)(0.9)}} \cdot 10^2 = 6$$

liquid film = 83% of total resistance

At bottom $M_H = \sqrt{\frac{3.6\times10^{-6}(2.6\times10^7)5}{(0.72)^2}} = 30$

$E_i = 1 + \frac{5(10^5)}{1000} = 501 \gg M_H \quad \therefore E = M_H = 30$

$$-r_A'''' = \frac{1}{\frac{1}{0.36} + \frac{10^5}{72(30)} + \frac{10^5}{2.6\times10^7(5)0.9}} \cdot 10^3 = 20.4$$

liquid film = 94%

Near the middle where $C_B = 30.56$. A mat. balance then gives $\begin{cases} p_A = 547\ \text{Pa} \\ Y_A = 0.0055 \end{cases}$

$M_H = \sqrt{\frac{3.6\times10^{-6}(2.6\times10^7)30.56}{(0.72)^2}} = 74$

$E_i = $ large

$\therefore E = M_H = 74$

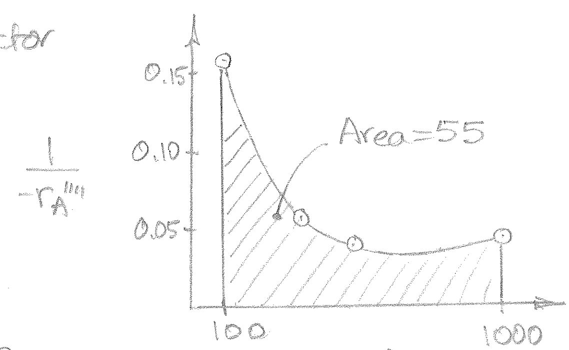
and $-r_A'''' = 25.4$

About 1/4 from the top where $p_A = 300$ Pa & $C_B = 44.4$ we find

$M_H = 89.5$, E_i = very large, so $E = M_H = 89.5$ & $-r_A'''' = 16.4$

So now to the performance of the reactor

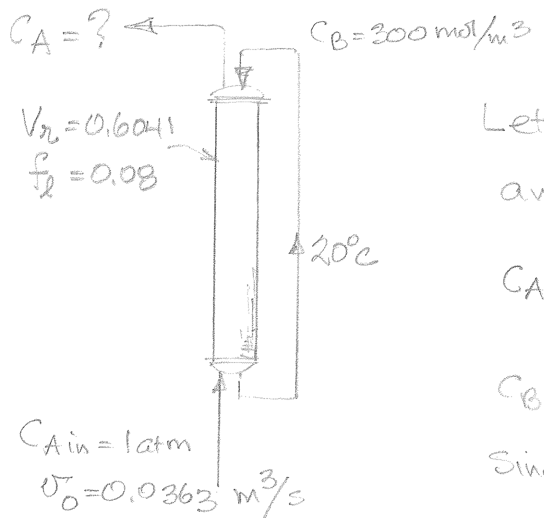
	p_A	$-r_A''''$	$1/-r_A''''$
Top	100	6	0.1667
1/4 from top	300	16.4	0.0610
Middle	547	25.4	0.0394
Bottom	1000	20.4	0.0490



$V_r = \frac{F_g}{\pi} \int \frac{dp_A}{-r_A''''} = \frac{90000}{10^5}(\text{area}) = \frac{90000}{10^5}(55) = 49.5\ m^3$

Liquid film resistance dominates, 83~94%

24.11



Let us start by evaluating C_A & C_B, and then the rate

$$C_{A_{in}} = \frac{p_{A_{in}}}{H_A} = \frac{101325}{3500} = 28.95\ mol/m^3$$

$C_{B_{in}} = 300\ mol/m^3$

Since $C_B \gg C_A$ we have an excess of B so we can take $C_B \cong$ constant $= 300$

Now to the rate of rx

$$M_H = \sqrt{\frac{1.4\times10^{-9}(0.433)300}{0.25/120}} = 2.05$$

$$E_i = 1 + \frac{300(3500)}{101325} = 11.36$$

since $E_i > 5\,M_H$ we have $E = M_H = 2.05$

so

$$-r_A'''' = \frac{1}{0 + \frac{3500}{0.025(2.05)} + \frac{3500}{0.433(300)0.08}} \cdot p_A$$

$$= \frac{p_A}{0 + 68292 + 337} = 1.457\times10^{-5}\,p_A = 1.4764$$

99.5% of the resistance

pure CO_2 at 1 atm, $\therefore p_A =$ constant, and $r_A'''' =$ const

From Eq 15

$$\frac{V_r}{F_{A0}} = \int_0^{X_A} \frac{dX_A}{-r_A''''} = \frac{X_A}{-r_A''''}$$

because $-r_A'''' =$ constant

$$\text{so} \quad X_A = \frac{V_r}{F_{A0}}(-r_A'''') = \frac{0.6041}{1.05}(1.48) = 0.8515 = 85\%$$

$F_{A0} = v_0 C_{A0} = 0.0363(28.95) = 1.05$

24.13 Here we have a batch agitated tank $k = 2.6\times10^5$ $H_A = 10^5$

At the beginning $C_B = 555.6$

$$M_H = \frac{\sqrt{3.6\times10^{-6}(2.6\times10^5)555.6}}{144/100} = 15.84$$

$$E_i = 1 + \frac{555.6(10^5)}{10^3} = 55561$$

guess this or something smaller
whatever we guess makes
no difference

Now $M_H \ll E_i$ so $E = M_H = 15.84$.

Next, since $E = M_H$ and $p_A \ll \pi$ we can use the shortcut just above Eq 19 to evaluate the rate. So

$$-r_A'''' = \frac{1}{\frac{\pi V_r}{F_g} + \frac{1}{k_{Ag}a} + \frac{H_A}{k_{Al}aE} + \frac{H_A}{kC_B f_l}} \cdot p_{A\,in}$$

$$= \frac{1}{\frac{10^5(1.62/0.9)}{9000} + \frac{1}{0.72} + \frac{10^5}{144(15.84)} + \frac{10^5}{2.6\times10^5(555.6)0.9}} \cdot p_A$$

$$= \frac{1}{20 + 1.3889 + 43.8417 + 0.0008} \cdot 1000 = 15.33$$

main resistances   negligible

or $\frac{1}{-r_A''''} = 0.06523$

At the end of the run $C_B = 55.56$

$$M_H = 5.01$$
$$E_i = 1 + \frac{55.6(10^5)}{10^3} = 5561$$

$E = M_H$
and again use the shortcut

$$-r_A'''' = \frac{1}{20 + 1.3889 + \underbrace{10^5/144(5.01)}_{138.61} + \sim 0} \cdot 1000 = 6.25$$

$$\therefore \frac{1}{-r_A''''} = 0.16$$

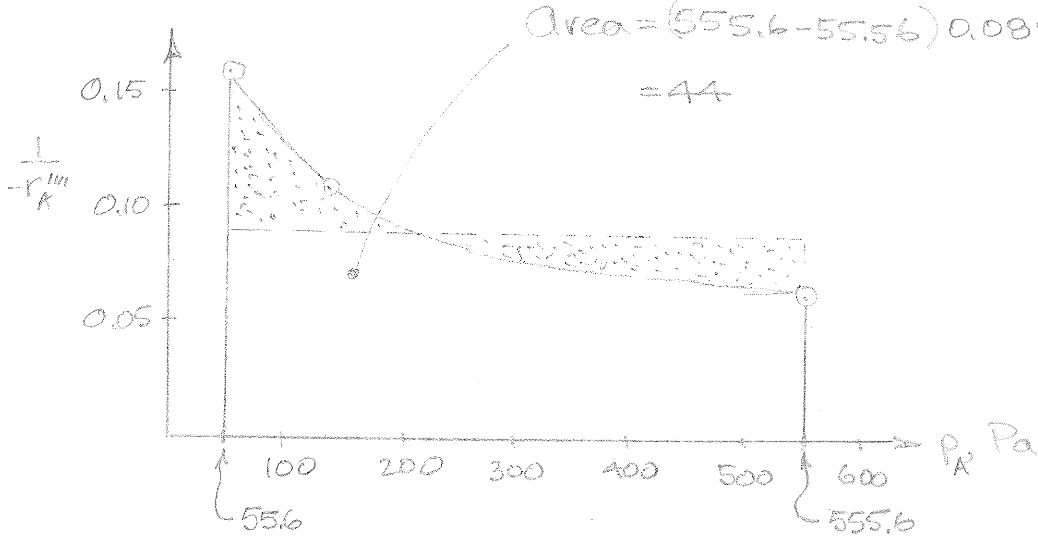
24.13 continued

At some intermediate condition, say at $C_B = \frac{555.6}{4} = 138.9$

$$\left.\begin{aligned} M_H &= \frac{15.84}{2} = 7.92 \\ E_i &= 55561/_4 = 13890 \end{aligned}\right\} E = M_H = 7.92$$

$$\therefore \quad -r_A'''' = \frac{1}{20 + 1.3889 + \frac{10^5}{144(7.92)} + \sim 0} \cdot 1000 = 9.168$$

and $\frac{1}{-r_A''''} = 0.109$



The length of time that we have to bubble gas through the liquid is

$$t = \frac{f_\ell}{b} \int \frac{dC_B}{-r_A''''} = f_\ell\,(\text{area}) = 0.9(44) = 39.6 \text{ hr}$$

$b = 1$

The minimum time needed if all the A reacts with B is

$$t_{min} = \frac{V_\ell\,(C_{B0} - C_{Bf})}{F_g\,(p_A/(\pi - p_A))} = \frac{1.62\,(555.6 - 55.56)}{9000\,(1000/99000)} = 8.91 \text{ hr}$$ a)

$\therefore$ Efficiency of use of A $= \frac{8.91}{39.6} = 22.5\%$ b)

24.15 Here we have a batch agitated tank with $k = 2.6\times10^3$, $H_A = 10^5$

At the beginning $C_B = 555.6\ \text{mol/m}^3$

$$\left.\begin{aligned} M_H &= \frac{\sqrt{2.6\times10^3(3.6\times10^{-6})555.6}}{144/100} = 1.584 \\ E_i &= 1 + \frac{555.6(10^5)}{\underbrace{10^3}_{\text{guess}}} = 55561 \end{aligned}\right\} E = M_H = 1.584$$

Use the shortcut formula just above Eq 19, thus

$$-r_A'''' = \frac{1}{\frac{V_R\pi}{F_g} + \frac{1}{k_{Ag}a} + \frac{H_A}{k_{Al}aE} + \frac{H_A}{kC_Bf_l}} \cdot p_{Ain}$$

$$= \frac{1}{\frac{(1.62/0.9)10^5}{9000} + \frac{1}{0.72} + \frac{10^5}{144(1.584)} + \frac{10^5}{2.6\times10^3(555.6)0.9}} \cdot 1000$$

$$= \frac{1}{20 + 1.3889 + 438.4 + \sim 0} \cdot 1000 = 2.175$$

$$\therefore \frac{1}{-r_A''''} = 0.460$$

At the end of the run $C_B = 55.56$

$$\left.\begin{aligned} M_H &= 1.584/\sqrt{10} = 0.5 \\ E_i &= 1 + \frac{55.56(10^5)}{\underbrace{10^3}_{\text{or smaller}}} = \text{big or bigger} \end{aligned}\right\} \therefore E = M_H = 0.5$$

Shortcut

$$-r_A'''' = \frac{1}{20 + 1.3889 + \underbrace{438.9(\sqrt{10})}_{1388} + \sim 0} \cdot 1000 = 0.7096$$

$$\therefore \frac{1}{-r_A''''} = 1.41$$

24.15 continued At some intermediate condition, say $C_B = 555.6/4 = 138.9$

$$\left.\begin{array}{l} M_H = 1.584/4 = 0.792 \\ E_i = 1 + \dfrac{555.6(10^5)}{10^3} = \text{big} \end{array}\right\} E = 1 + \frac{M_H^2}{3} = 1.2$$

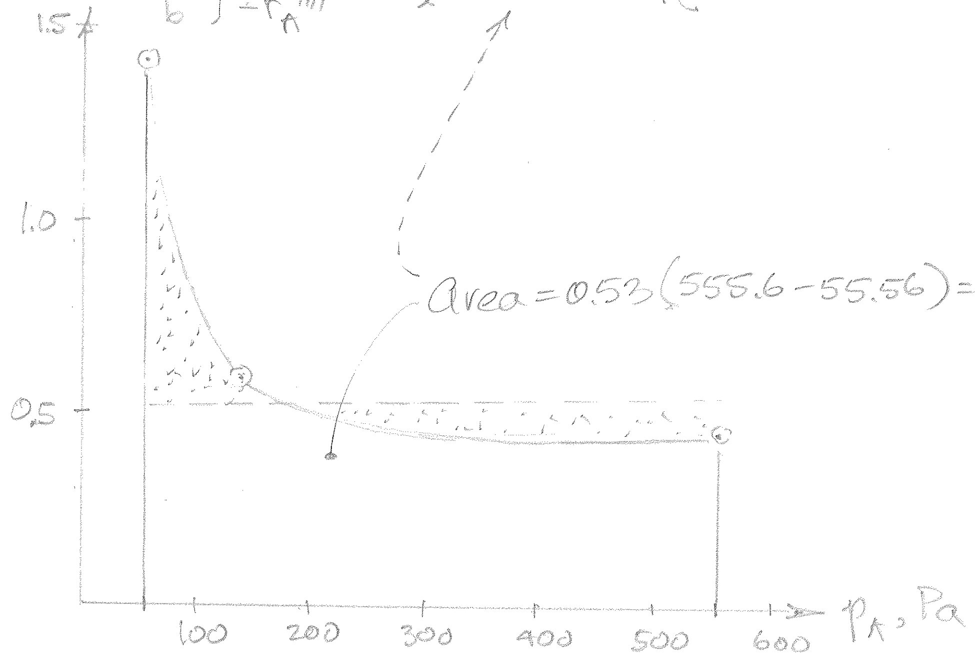
$$\therefore\ -r_A'''' = \frac{1}{20 + 1.3889 + 10^5/144(1.2)} \cdot 1000 = 1.666$$

main resistance

$$\therefore\ \frac{1}{-r_A} = 0.600$$

The length of time needed to bubble gas through the reactor is

$$t = \frac{f_l}{b}\int \frac{dC_B}{-r_A''''} = f_l\,(\text{area}) = 0.9(265) = 238.5\,\text{hr} \quad \text{(a)}$$



$$t_{min} = \frac{V_l\,(C_{B0} - C_{Bf})}{F_g\,(p_{Ain}/(\pi - p_{Ain}))} = \frac{1.62(555.6 - 55.56)}{9000(1000/99000)} = 8.91\,\text{hr}$$

$$\therefore\ \text{Efficiency of use of A} = \frac{8.91}{238.5} = 3.7\% \quad \text{(b)}$$