22.1 First let us see if either extreme with its simplifications apply

$$C_A^* = \frac{p_A}{H_A} = \frac{1013250}{86000} = 11.78$$ constant throughout

At inlet $C_{B0} = 400\ \text{mol/m}^3$

guess $X_B \leq 90\%$ $C_B = 40\ \text{mol/m}^3$

Even up to $X_B = 0.9$ we have the extreme where $C_B \gg C_A$. Let us use the expressions for this extreme, but then check it at the end

Evaluate quantities needed to find the rate

$$a_c = \frac{6 f_s}{d_p} = \frac{6(0.58)}{5\times10^{-3}} = 696\ \text{m}^2/\text{m}^3$$

$$\therefore k_c a_c = (3.86\times10^{-5})(696) = 0.0269\ \text{s}^{-1}$$

$$M_T = L\sqrt{\frac{k'\rho_s}{\mathscr{D}}} = \frac{5\times10^{-3}}{6}\sqrt{\frac{(1.77\times10^{-5})(1800)}{4.16\times10^{-10}}} = 7.3 \quad \dots \therefore \mathcal{E} = 0.13$$

Now to the rate equation

$$-r_A'''' = \frac{1}{\frac{1}{86000(10^{-4})} + \frac{1}{0.02} + \frac{1}{0.0269} + \frac{1}{(1.77\times10^{-5})(1800)(0.13)(0.58)}} \cdot \frac{1013250}{86000}$$

$$= \frac{1}{\underbrace{0.116}_{\text{negligible}} + 50 + 37.17 + \underbrace{416.3}_{\text{main resistance}}} \cdot \frac{1013250}{86000} = 0.0234$$

With constant p_A throughout the trickle bed and with the rate independent of C_B the material balance becomes very simple, as with a mixed flow reactor. Thus

$$F_{A0} X_A = F_{B0} X_B = (-r_A'''') V_r$$

$$F_{B0} = v_\ell C_{B0} = (2\times10^{-4})(400) = 0.08\ \text{mol/s}.$$

$$\therefore X_B = \frac{(-r_A'''') V_r}{F_{B0}} = \frac{(0.0234)(5\times0.1)}{0.08} = 0.146 \cong \underline{15\%}$$

this is < 90%, so it satisfies our assumption

22.3 This reaction is in mixed flow, so evaluate terms

$$a_c = \frac{6 f_s}{d_p} = \frac{6(0.0056)}{10^{-5}} = 3360 \frac{m^2}{m^3}, \qquad k_{Ac} a_c = 10^{-3}(3360) = 3.36\ s^{-1}$$

$$C_A = \frac{p_A}{H_A} = \frac{200(101325)}{2.776\times 10^5} = 73 \frac{mol}{m^3} \cdots \text{stays constant}$$

$$C_B = 2000 \frac{mol}{m^3}$$

in any case $C_B \gg C_A$

So consider this to be a 1st order reaction with respect to A, or

$$-r_A = (5.96\times 10^{-6} C_A^{-0.4} C_{Bf}) C_A$$

$$M_T = \frac{d_p}{6}\sqrt{\frac{n+1}{2}\cdot\frac{k' C_A^{-0.4} C_{Bf}}{\mathcal{D}}} = \frac{10^{-5}}{6}\sqrt{\frac{1.6}{2}\cdot\frac{(5.97\times 10^{-6})(73)^{-0.4} C_{Bf}\times 8900}{2\times 10^{-9}}}$$

$$= 0.003258\, C_B^{1/2}, \text{ even at } C_B = 2000,\ M_T < 1 \ \therefore\ \mathcal{E}_A = 1$$

Now to the rate

$$r_A'''' = \frac{1}{\frac{1}{0.05} + \frac{1}{3.36} + \frac{1}{(5.96\times 10^{-6})73^{-0.4} C_{Bf}(1)(0.0056)8900}} \cdot \frac{101325\times 200}{2.776\times 10^5}$$

main resistance

$$= \frac{73}{20.2976 + 1872.6/C_B}$$

Now make a material balance $F_{A0}X_A = F_{B0}X_B = (-r_A'''')V_{reactor}$

not useful; $v_\ell (C_{B0} - C_B) \cdots$ useful.

$$\therefore\ 10^{-2}(2000 - C_B) = \frac{73}{(20.2976 + 1827.6/C_B)}\cdot 2 \quad \cdots \text{ or } 2000 - C_B = \frac{14600}{(20.9276 + 18728.6/C_B)}$$

Solve for C_B by trial and error

Guess C_B	LHS	RHS
1700	300	466
1400	600	433
1560	440	452
1550	450	451 ← ok

$\therefore C_B = 1550$ mol/m³

and $X_B = 1 - \frac{1550}{2000} = 22.5\%$ ←

Note: We can use larger particles, or even less particles without lowering X_B significantly because the main resistance in the rate expression is in the mass transfer steps. To improve the conversion either increase the mass transfer steps, or better still increase the pressure.

22.5 First let us see if either extreme applies

$$C_A = \frac{p_A}{H_A} = \frac{101325}{28500} = \underset{\text{constant}}{3.555} \text{ mol/m}^3$$

At start: $C_{B0} = 1097 \text{ mol/m}^3$

At end of run $C_{Bf} = 109.7 \text{ mol/m}^3$

Comparing we see that $C_B \gg C_A$ throughout the run.

Use the equations for the $C_B \gg C_A$ extreme

$$a_c = \frac{6 f_s}{d_p} = \frac{6(0.25)}{3\times10^{-4}} = 5000 \frac{m^2}{m^3}$$

$$k_{Ac} a_c = 10^{-5}(5000) = 0.05 \text{ s}^{-1}$$

$$M_T = L\sqrt{\frac{k' \rho_s}{\mathscr{D}}} = \frac{3\times10^{-4}}{6}\sqrt{\frac{0.05(750)}{8.35\times10^{-10}}} = 10.6 \qquad \therefore \mathcal{E} = \frac{1}{10.6} = 0.0944$$

We are now ready to write the rate expression

$$-r_A'''' = \frac{1}{\frac{1}{0.04} + \frac{1}{0.05} + \frac{1}{0.05(750)(0.0944)(0.25)}} \cdot \frac{101325}{28500}$$

$$= \frac{1}{25 + 20 + 1.13}(3.555) = 0.0771 \text{ mol A/m}^3 \text{ reactor} \cdot \text{s}$$

Finally go to the material balance. Writing it for A

$$\underbrace{F_{A0} X_A}_{\text{useless}} = \underbrace{\frac{V_l}{b}\left(-\frac{dC_B}{dt}\right) = (-r_A'''')V_r}_{\text{use these terms to integrate}}$$

$$t = \frac{V_l (C_{B0} - C_B)}{b V_r (-r_A'''')} = \frac{0.65(1097 - 109.7)}{2/3\,(1)(0.0771)} = 12{,}485 \text{ s}$$

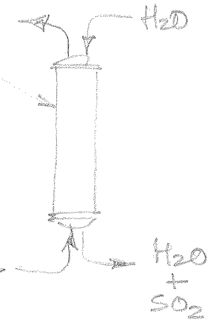
$$= 3 \text{ hr } 28 \text{ min}$$

22.7 Preliminary $SO_2 + \frac{1}{2}O_2 \longrightarrow \cdots$
$A + \frac{1}{2}B \longrightarrow \cdots$

$-r_A' = 0.01553\, C_B$, mol/kg·s

$-r_B' = -\frac{1}{2} r_A' = 0.007765\, C_B$, mol/kg·s

$V_r = 0.2\, m^3$



$p_A = 0.002(101325)$ Pa
$p_B = 0.21\,(101325)$ Pa
$\pi = 1$ atm
$v_0 = 0.01\, m^3/s$

In terms of concentrations

$$C_{A\,in} = \frac{p_A}{H_A} = \frac{0.002(101325)}{380000} = 5.333 \times 10^{-4} \text{ mol/m}^3$$

$$C_{B\,in} = \frac{p_B}{H_B} = \frac{0.21\,(101325)}{78000} = 2446 \times 10^{-4} \text{ mol/m}^3$$

Note that $p_A \ll p_B$ & $C_A \ll C_B$

This is a puzzling problem because
- the chemical rate depends on B
- but A provides the mass mass transfer resistance

Let me guess that the overall rate is limited (or determined) by A, not B, thus is mass transfer controlled. If I am wrong then I will make the other assumption

Guess that the transfer of A controls the overall rate. Also, since $C_B \approx 500\, C_A$ we can reasonably assume that C_B stays constant throughout the operation.

So write the chemical rate in terms of C_A. At inlet conditions

$$-r_{A\,inlet}' = k' C_A^0 C_B^1 = \left(k' \frac{C_B}{C_A}\right) C_A = \left(k' \frac{p_B}{p_A} \cdot \frac{H_A}{H_B}\right)$$

$$= \left(0.01553 \frac{21}{0.2} \frac{380000}{87000}\right) C_A = \underbrace{7.122}_{m^3/kg\cdot s}\, C_A \text{ mol/kg·s}$$

Now the overall rate in the tower is

$$-r_A'''' = \frac{1}{\dfrac{1}{(k_i a_i)_{l+g}} + \dfrac{1}{k_{Ac} a_c} + \dfrac{1}{k' \rho_s \varepsilon_A f_c}} \cdot \frac{p_A}{H_A} \qquad \text{--- (i)}$$

Evaluate terms

22.7 continued

$$(k_i a_i)_{l+g} = 0.01\ s^{-1}$$

$$a_c = \frac{6 f_s}{d_p} = \frac{6(0.6)}{0.005} = 720\ m^2/m^3$$

$$k_c = 4\times10^{-5}\ m/s$$

$$M_T = \frac{d_p}{6}\sqrt{\frac{k' \rho_s}{\mathcal{D}}} = \frac{0.005}{6}\sqrt{\frac{7.122(850)}{5.35\times10^{-10}}} = 2803$$

$\mathcal{E} = 357\times10^{-6}$ ... strong pore diffusion resistance

Replace in (i)

$$-r_A'''' = \frac{1}{\underset{s^{-1}}{\frac{1}{0.01}} + \frac{1}{\underset{m/s}{4\times10^{-5}}\underset{m^2/m^3}{(720)}} + \frac{1}{\underset{m^3/kg\cdot s}{7.122}\underset{kg/m^3\,solid}{(850)}\underset{(-)}{(357\times10^{-6})}\underset{m^3\,solid/m^3}{(0.6)}}} \overbrace{\frac{0.002(101325)}{380000}}^{C_A}$$

$$= \frac{1}{100+34.7+0.77} C_A$$

Note that the mass transfer resistance (100+34.7) is much greater than that of reaction (0.77), so our original guess is justified. Continue with the performance equation.

For plug flow

$$\frac{V_r}{v_0} = \frac{0.2m^3}{0.01m^3/s} = \int_{C_A}^{C_{A0}} \frac{dC_A}{-r_A''''} = \int_{C_A}^{C_{A0}} \frac{dC_A}{0.0074 C_A} = \frac{1}{0.0074}\ln\frac{C_{A0}}{C_A}$$

$$\therefore \frac{C_A}{C_{A0}} = e^{-V_r(0.0074)/v_0} = e^{-0.2(0.0074)/0.01} = 0.862$$

$\therefore$ the conversion of SO_2 $X_{SO_2} = X_A = 14\%$