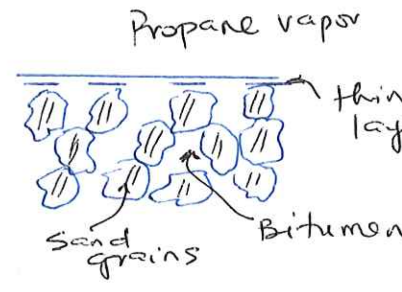
ENCH 501 Transport Phenomena University of Calgary Name________________________________

Quiz #6 / Time Allowed: 45 minutes Use of cheat sheet allowed. December 2, 2014 aJ

VAPEX, vapor extraction of heavy crude oil and bitumen, involves contacting vapors of light hydrocarbons (propane to hexane) with oils of low mobility in reservoirs. The light hydrocarbon dissolves in and lowers the viscosity of the heavy oil or bitumen such that it can flow or can be displaced towards a production well. (**Das and Butler**, Can. J. Chem. Engg, 74, 985-992, 1996)

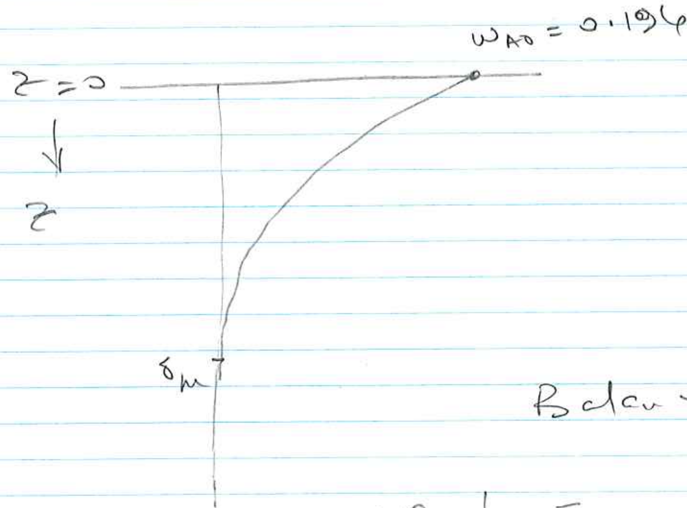
In a laboratory experiment, a sand bed that has been fully saturated with bitumen fills a rectangular box. The top surface of the box is open, covered entirely with a thin layer of bitumen above the porous sand bed (see sketch), and is suddenly exposed to pure propane vapor. The entire system is maintained at 35°C and 1.16 MPa. The thin top layer is immediately saturated with propane. The mass fraction, ω_{Ao}, of the propane in the thin layer remained constant at 0.196. (Mass fraction is used because the chemical composition of the bitumen is not known.) The porosity of the bed, ε, equals 0.28. From the thin layer, propane diffused into the bed. The diffusivity of propane in bitumen is given as $8(10^{-9})$ m^2/s.



(a) Obtain an expression for the profile of mass fraction of propane in the bitumen as a function of distance from the surface and time, $\omega_A(z,t)$ using **the integral method**. Show your steps.
(b) If the bed is 0.6 m deep, after how long will propane have penetrated to the bottom of the bed?
(c) At the instant calculated for part (b), how much propane (kg/m^2 surface area) would be in the bitumen?

Assume the density of bitumen with varying amounts of propane is constant at 928 kg/m^3. Also assume that the original bitumen did not contain propane, there are no reactions and no component of bitumen diffuses.

ENCH 501 Solution Quiz 6 Dec. 2, 2014



On mass basis, the flux is

$$n_A = -\rho D_{AB} \frac{d\omega_A}{dz} + \omega_A(n_A + \underbrace{n_B}_{0})$$

Balance / unit area of surface.

$$n_A\Big|_{z=0} = \frac{d}{dt}\left[\int_0^{\delta_m} \varepsilon \rho \omega_A \, dz\right]$$

$$\left(-\frac{\rho D_{AB}}{1-\omega_A}\frac{d\omega_A}{dz}\right)_{z=0} = \frac{d}{dt}\left[\int_0^{\delta_m} \varepsilon \rho \omega_A \, dz\right]$$

since ρ = const, remove.

$$-\frac{D_{AB}}{1-\omega_{A0}}\frac{\partial \omega_A}{\partial z}\Big|_{z=0} = \frac{d}{dt}\left[\int_0^{\delta_m} \varepsilon \omega_A \, dz\right]$$ Integral eq.

Conditions:

$z = 0 \quad \omega_A = \omega_{A0}$

$z = \delta_m \quad \frac{d\omega_A}{\partial z} = 0$

$w = \delta_m \quad \omega_A = 0$

$$\frac{\omega_A}{\omega_{A0}} = \left(1 - \frac{z}{\delta_m}\right)^2.$$

assume

$$\omega_A = a + bz + cz^2$$

$$\omega_A = \omega_{A0}\left(1 - 2\frac{z}{\delta_m} + \left(\frac{z}{\delta_m}\right)^2\right)$$

$$\frac{d\omega_A}{dz} = \omega_{A0}\left(-\frac{2}{\delta_m} + \frac{2z}{\delta_m^2}\right)$$

$$\frac{d\omega_A}{dz}\Big|_{z=0} = -\frac{2\omega_{A0}}{\delta_m}$$

$$-\frac{D_{AB}}{1-\omega_{A0}}\left(-\frac{2\omega_{A0}}{\delta_m}\right) = \frac{d}{dt}\left[\int_0^{\delta_m} \varepsilon\,\omega_{A0}\left(1-\frac{2z}{\delta_m}+\frac{z^2}{\delta_m^2}\right)dz\right]$$

$$= \frac{d}{dt}\left[\varepsilon\,\omega_{A0}\,\delta_m \int_0^1 \left(1-2\eta+\eta^2\right)d\eta\right]$$

$$\left(\eta-\eta^2+\frac{1}{3}\eta^3\right)$$

$$= \frac{d}{dt}\left[\varepsilon\,\omega_{A0}\frac{\delta_m}{3}\right]$$

$$\frac{6 D_{AB}}{\varepsilon(1-\omega_{A0})} = \delta_m \frac{d\delta_m}{dt} = \frac{1}{2}\frac{d\delta_m^2}{dt}$$

with $t=0$ $\delta_m=0$

$$\delta_m = \sqrt{\frac{12 D_{AB}}{\varepsilon(1-\omega_{A0})}\cdot t}$$

(b) If $\delta_m = 0.6$ m.

$$0.6 = \sqrt{\frac{12(8)(10^{-9})t}{0.28(1-0.196)}}$$

$t = 8.442(10^5)$ s $= 234.5$ hrs or 9.77 days

(c) Total propane present / m^2 area at surface

$$Q = \int_0^{\delta_m} \rho \varepsilon w_A \, dz$$

$$w_A = w_{A0}\left(1 - z/\delta_m\right)^2$$

$$Q = \int_0^{\delta_m} \rho \varepsilon w_{A0} (1-\eta)^2 \delta_m \frac{dz}{\delta_m}$$

$$= \rho \varepsilon w_{A0} \delta_m \int_0^1 (1 - 2\eta + \eta^2)\, d\eta$$

$$= \frac{\rho \varepsilon w_{A0} \delta_m}{3} =$$

$$= \frac{928 (0.28)(0.196)(0.6)}{3} = 10.18 \ \text{kg}/m^2$$

$$\frac{kg}{m^3} \cdot m$$