Problem 1 (13 points)

Please answer the questions listed below:

(a) Explain the difference(s) between the molecular transport and convective transport processes. **(3 points)**

(b) Why do we introduce the "overall mass transfer coefficients" to estimate the mass/molar fluxes? **(3 points)**

(c) How do we apply the "Reynolds analogy"? **(3 points)**

(d) What's the Fourier's first law of heat conduction? **(1 point)** & What's the counterpart of it in momentum transport? **(1 point)**

(e) What's the Fourier's second law of heat conduction? **(1 point)** & What's the counterpart of it in mass transport? **(1 point)**

Problem 2 (20 points)

You are asked to analyze a one-dimensional (x-direction), steady-state, incompressible, hydrodynamically fully-developed laminar flow through a parallel plate channel, which is shown in **Figure 1.**

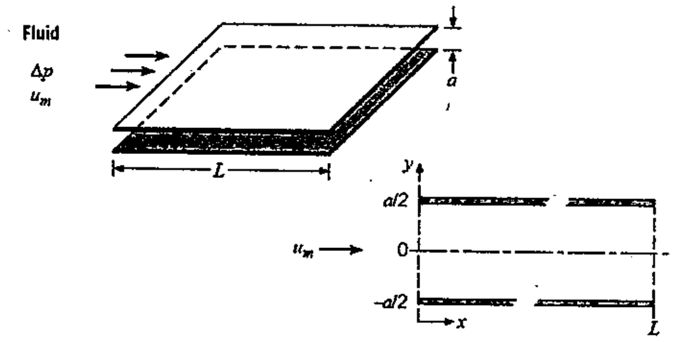

Figure 1. A schematic diagram of the system in Problem 2.

(a) **(4 points)** By applying appropriate assumptions and performing shell momentum balance, please show that the x-momentum equation has the form:

$$\mu\frac{d^2u}{dy^2} = \frac{dP}{dx} = \text{constant}$$

and explain the reason why both terms are constant

(b) **(6 points)** Please show that the velocity profile $u(y)$ and average (or mean) velocity u_m are of the forms:

$$u(y) = \frac{3}{2}u_m[1 - \frac{y^2}{(a/2)^2}]$$

$$u_m = -\frac{a^2}{12\mu}\left(\frac{dP}{dx}\right) = \frac{a^2}{12\mu}\left(\frac{\Delta P}{L}\right)$$

(c) **(6 points)** Define the hydraulic diameter D_h. Write an expression defining the "Moody friction factor" f and Reynolds number Re_{Dh} using the hydraulic diameter as the characteristic length for the parallel-plate channel described here.

(d) **(4 points)** The Moody friction factor can be estimated from the expression,

$$f = \frac{C}{Re_{D_h}}$$

where C depends upon the flow cross section. What is the coefficient C for the parallel-plate channel described here?

Problem 3 (21 points)

As shown in **Figure 2**, a catalytic surface is placed in a gas stream to promote a heterogeneous chemical reaction involving species A. Assume that the reaction produces species A at a rate R''_A, which is defined as the molar rate of production of A per unit surface area of the catalyst. Once steady-state conditions are reached, the rate of species transfer from the surface, $N''_{A,x}$ must equal the surface reaction rate:

$$N''_{A,x} = R''_A$$

It is assumed that species A leaves the surface as a result of one-dimensional transfer through a thin film of thickness L and that no reactions occur within the film itself. Assume the medium to be stationary, and total concentration (C) and diffusion coefficient (D_{AB}) to be constant. The mole fraction of A equals $x_{A,L}$ at $x = L$, whereas the surface reaction (R''_A) occurring on the catalytic surface (at $x = 0$) follows the first-order kinetics with a reaction rate constant k''.

$$R''_A = -k'' C_A(0)$$

(a) **(2 points)** What is the unit of k''?

(b) **(6 points)** Use the assumptions, equation of continuity of species A (see below), and the relationship between the absolute molar flux of A, $N''_{A,x}$, diffusive molar flux of A, $J^*_{A,x}$, and x_A to obtain the second order differentiation of x_A with respect to x.

(c) **(4 points)** List appropriate boundary conditions. Use these conditions and the equation obtained in (b), please show how you can obtain the distribution/profile of x_A shown below:

$$\frac{x_A(x)}{x_{A,L}} = \frac{1 + (xk''/D_{AB})}{1 + (Lk''/D_{AB})}$$

(d) **(3 points)** Please prove that $N''_{A,x}$ at $x = 0$ is of the form shown below:

$$N''_{A,x}(0) = -\frac{k'' C x_{A,L}}{1 + (Lk''/D_{AB})}$$

(e) **(3 points)** If the process is "reaction limited" (i.e., $k'' \to 0$), determine the values or expressions of $x_A(0)/x_{A,L}$ and $N''_{A,x}(0)$?

(f) **(3 points)** If the process is "diffusion limited" (i.e., $k'' \to \infty$), determine the values or expressions of $x_A(0)/x_{A,L}$ and $N''_{A,x}(0)$?

Hint: Equation of continuity of species A for a multicomponent mixture:

$$-\vec{\nabla} \cdot \vec{N}''_A + R'''_A = \frac{\partial C_A}{\partial t}$$

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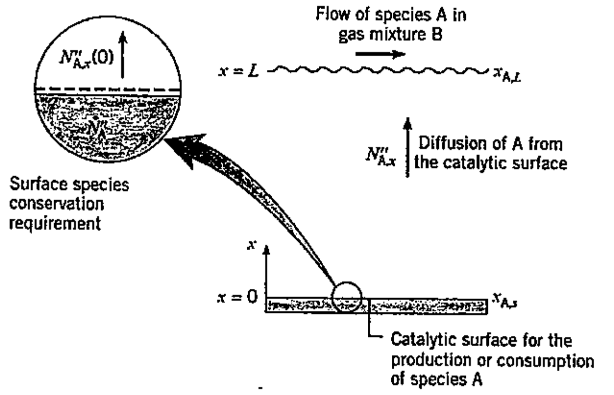
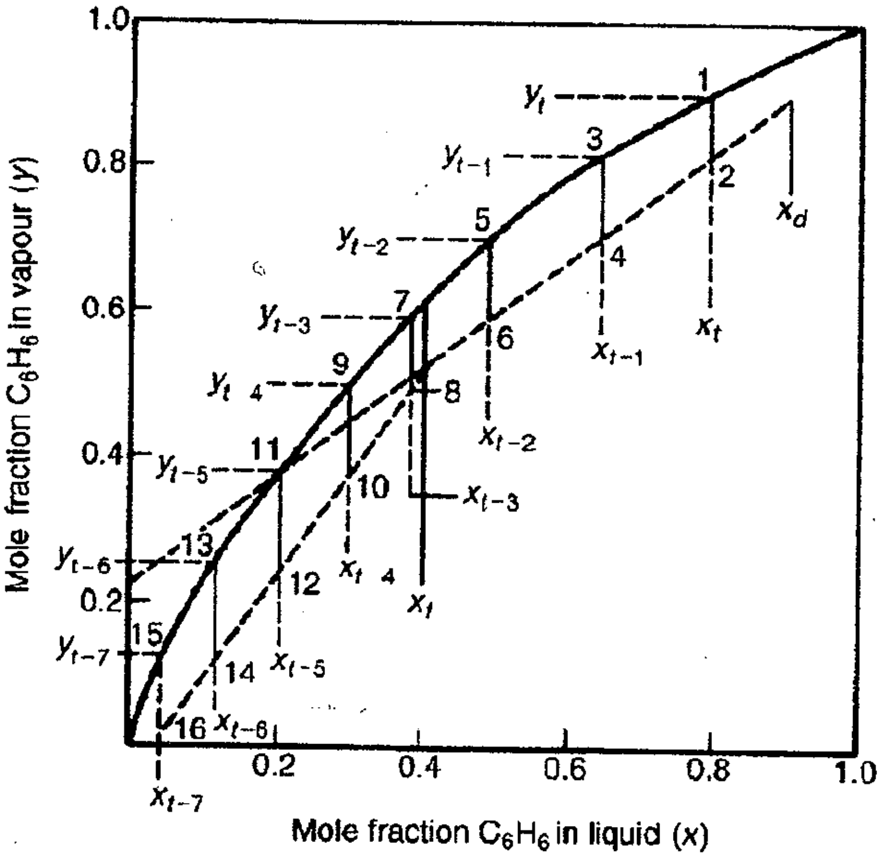


Figure 2. A schematic diagram of the system in Problem 3.

Problem 4 (10 points)

A mixture of benzene and toluene containing 40 mole per cent benzene is to be separated to give a product containing 90 mole per cent benzene at the top, and a bottom product containing not more than 10 mole per cent benzene. The feed enters the column at its boiling point, and the vapor leaving the column which is condensed but not cooled, provides reflux and product. It is proposed to operate the unit with a reflux ratio of 3 kmol/kmol product. It is required to find the number of theoretical plates needed and the position of entry for the feed. The equilibrium diagram at 100 kN/m^2 is shown in the figure below. (Note: Use Lewis-Sorel Method that is calculate the answer by the operating lines numerically, do not use McCabe-Thiele Method.)



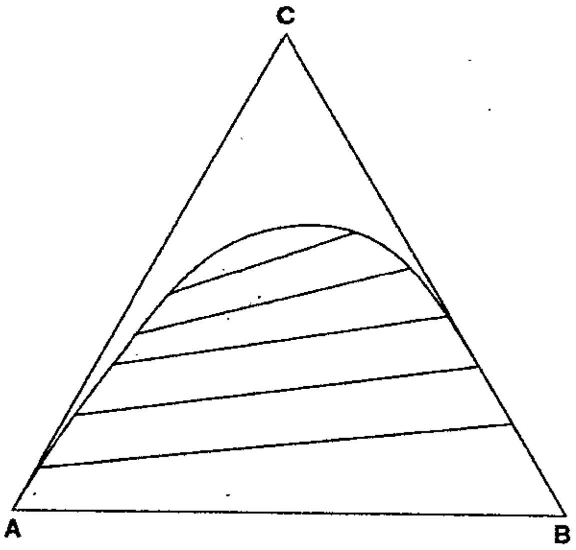
Problem 5 (8 points)

A bubble-cap column with 30 plates is to be used to remove n-pentane from a solvent oil by means of steam stripping. The inlet oil contains 6 kmol of n-pentane per 100 kmol of pure oil and it is desired to reduce the solute content to 0.1 kmol per 100 kmol of solvent. Assuming isothermal operation and an overall plate efficiency of 30%, find the specific steam consumption **(2 points)**, that is the kmol of steam required per kmol of solvent oil treated, and the ratio of the specific and minimum steam consumptions **(4 points)**. How many plates would be required if this ratio were 2.0? **(2 points)**

Note: The equilibrium relation for the system may be taken as $Y_e = 3.0X$, where Y_e and X are expressed in mole ratios of pentane in the gas and liquid phases respective.

Problem 6 (4 points)

A 50 per cent solution of solute C in solvent A is extracted with a second solvent B in a countercurrent multiple contact extraction unit. The mass of B is 25 per cent of that of the feed solution.
Determine the number of ideal stages required and the mass and concentration of the first extract if the final raffinate contains 15% of solute C.



Problem 7 (3 points)

The constants in the Antoine equation are:

For benzene: $k_1 = 6.90565$ $k_2 = 1211.033$ $k_3 = 220.79$

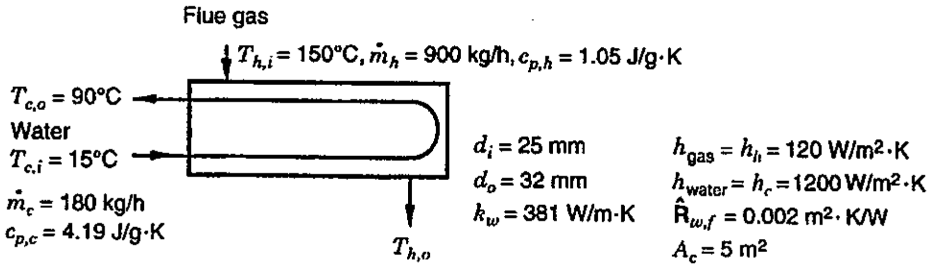
For toluene: $k_1 = 6.95334$ $k_2 = 1343.943$ $k_3 = 219.377$

where P^o is in mm Hg, T is in °C and $\log_{10}$ is used instead of $\log_e$.
Determine the vapor phase composition of a mixture in equilibrium with a liquid mixture of 0.5 mole fraction benzene and 0.5 mole fraction of toluene at 338 K. Will the liquid vaporize at a pressure of 101.3 kN/m^2?

Antoine equation : $lnP^0 = k_1 - \frac{k_2}{T+k_3}$

Problem 8 (10 points)

In a shell-and-tube feedwater heater, cold water at 15°C flowing at the rate of 180 kg/h is preheated to 90°C by flue gases from 150°C flowing at the rate of 900 kg/h. The water flows inside the copper tubes ($d_i = 25$ mm, $d_0 = 32$ mm) having thermal conductivity $k_w = 381$ W/m·K. The heat transfer coefficients on gas and water sides are 120 and 1200 W/m^2·K, respectively. The fouling factor on the water side is 0.002 m^2·K/W. Determine the flue gas outlet temperature, the overall heat transfer coefficient based on the outside tube diameter, and the true mean temperature difference for heat transfer. Consider specific heats c_p for flue gases and water as 1.05 and 4.19 J/g·K respectively, and the total tube outside surface area as 5 m^2. There are no fins inside or outside the tubes, and there is no fouling on the gas side.



Problem 9 (4 points)

A gas-to-air crossflow waste heat recovery exchanger, having both fluids unmixed, has NTU = 6 and $C^* = 1$. The inlet fluid temperatures on the hot and cold sides are 360°C and 25°C, respectively. Determine the outlet fluid temperatures with and without longitudinal wall heat conduction. Assume that $\lambda_c = \lambda_h = 0.04$, and $(\eta_o hA)_h = (\eta_o hA)_c = 1$.

Problem 10 (4 points)

It is desired to cool down 0.34 kg/s of an aqueous solution with a heat capacity similar to water from 60 to 50°C. The cooling fluid will be 0.3 kg/s of water at 25°C. A double-pipe heat exchanger will be used. The external diameter of the interior tube is 0.025 m. The overall heat transfer coefficient is estimated as 1,600 W/(m^2·K). Calculate the necessary tube length if

(a) A countercurrent arrangement is used. **(2 points)**

(b) A co-current arrangement is used. **(2 points)**

Problem 11 (3 points)

A mercury-in-glass thermometer having ε = 0.9 hangs in a metal building and indicates a temperature of 20°C. The walls of the building are poorly insulated and have a temperature of 5°C. The value of h for the thermometer may be taken as 8.3 W/m^2·°C. Calculate the true air temperature.

$(\sigma = 5.669 \times 10^{-8}\ W/m^2 \cdot K^4)$