MANICALAND STATE UNIVERSITY OF APPLIED SCIENCES

FACULTY OF ENGINEERING

Chemical and Processing Engineering Department

CHEMICAL REACTION ENGINEERING II

CODE: HCHE 312

SESSIONAL EXAMINATIONS

APRIL-MAY 2021

DURATION: 3 HOURS

EXAMINER: DR M. CHIGONDO

INSTRUCTIONS

1. Answer all four questions
2. Each question carries 25 marks
3. Total marks 100

QUESTION ONE

(a) (i) Define the *Hatta modulus* in words and explain its significance in the choice of reactor system for the reaction, $A(l \rightarrow g) + B(l) \rightarrow R(l)$. [2]

(ii) Explain the use of an *enhancement factor* in determining the overall rate for this reaction [2]

(iii) Describe the physical origin of this enhancement factor [2]

(b) Gaseous ammonia (A) is to be absorbed and reacts with nitric acid (B) as follows:

$A(l \rightarrow g) + B(l) \rightarrow R(l)$, $r_{Al} = kC_A C_B$ in a packed column

Given that:

$p_A = 100$ Pa and $C_B = 100$ mol/m^3 liquid

$k = 10^{-2}$ m^3/mol^2.h

$k_{Ag} = 0.01$ mol/h.m^2 of reactor.Pa

$a = 100$ m^2/m^3 of reactor

$k_{Al}\,a = 100$ m^3 liquid / (m^3 reactor h)

$H_A = 10^5$ (Pa m^3 liquid)/mol

$f_l = 0.1$ m^{3}liquid/m^{3}reactor

$$\mathscr{D}_{Al} = \mathscr{D}_{Bl} = 10^{-6}\ \mathrm{m^2/hr}$$

(i) Calculate the resistances in gas and liquid films and in the bulk liquid and locate the major resistance.

(ii) Locate the reaction zone [7]

(iii) Is the reaction pseudo-first order? Explain your answer. [6]

(iv) Calculate the rate of reaction in mol/hr m^3 (react). [3]

(v) What reactor type would be suitable for these reaction conditions? Explain your answer. [3]

QUESTION TWO

Fig. 1. Shows a blast furnace fluid-particle contactor for counter current reaction by the progressive core model.

Fig. 1: Blast furnace

One of the reactions taking place in this contactor is:

$C\ (s) + O_2\ (g) \rightarrow CO_2(g)$

(i) Describe the *shrinking core* model reaction of the above reaction [8]

(ii) Calculate the time required for complete combustion of carbon particles for which the reaction proceeds according to the shrinking particle model, if the graphite particles (radius 5 mm and density of 2200 kg/m^3) are exposed to a high-velocity 8%-oxygen stream at 1173 K and 1 atm. The rate constant is 20 cm/s [5]

Particles are treated in a noncatalytic gas-solid reactor in which there is some mixing. The reaction proceeds according to the shrinking core model with reaction control and time for complete conversion of the (3 mm diameter) particles is 8 minutes. The reactor has a residence time distribution for 3 mm particles as tabulated below

(b) For the gas-liquid reaction, $A(l \rightarrow g) + B(l) \rightarrow R(l)$ and with C_{Ai} comparable with C_{Bl} , sketch the concentration profiles of A and B in the liquid film and bulk for the following situations, indicating where the reaction takes place:

(i) Instantaneous reaction [3]

(ii) Fast reaction, such that the Hatta modulus > 2 [3]

(iii) Very slow reaction such that the Hatta modulus < 0.02 [3]

For each case, name one type of reactor which would be suitable and explain your choice.

(c) State three factors to consider when selecting a contactor [3]

QUESTION THREE

(a) The following is the general rate equation for fluid-fluid reactions, State the meaning each of the symbols in the equation [9]

$$-r_A'''' = \frac{1}{\underbrace{\frac{1}{k_{Ag}a}}_{\text{gas film resistance}} + \underbrace{\frac{H_A}{k_{Al}aE}}_{\text{liquid film resistance}} + \underbrace{\frac{H_A}{kC_B f_l}}_{\text{liquid bulk resistance}}} p_A$$

(b) Fig. 2 a graphical illustration absorption of A in the liquid and reaction in the liquid, based on the two-film theory

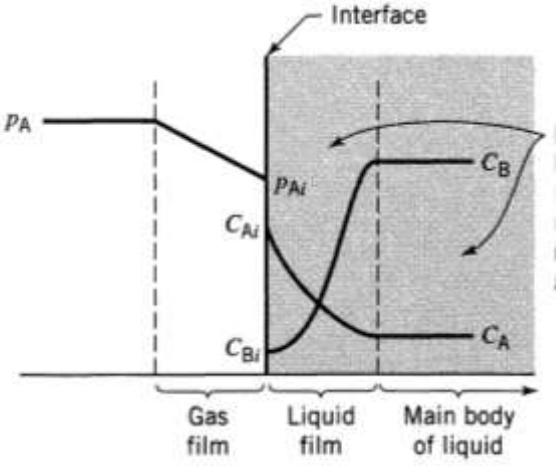


Fig. 2: Absorption of A in the liquid and reaction in the liquid, based on the two-film theory

Explain the variation of the following as the reaction proceeds: [6]

(i) the partial pressure (p_A)

(ii) C_A and

(iii) C_B

(c) State the case shown by the illustration in Fig 2 [1]

(d) Explain the following: (i) *gas film resistance* (ii) *liquid film resistance* [2]

(e) (i) State the three factors control the design of a fluid-solid reactor [3]

(ii) A feed consisting: 20% of 20-μm-radius particles, 60% of 40-μm-radius particles and 20% of 80-μm-radius particles is to be fed continuously in a thin layer onto a moving grate crosscurrent to a flow of reactant gas. For the planned operating conditions, the time required for complete conversion is 5, 10, and 20 min for the three sizes of particles. Find the conversion of solids on the grate for a residence time of 8 min in the reactor. [4

QUESTION FOUR

(a) State the type of contactor for the following situations:

(i) If the liquid film dominates

(ii) If the resistance is in the main body of the liquid

(iii) Relative flow rates of about F_l/F_g, is 10 at 1 bar [3]

(b) An engineering process plans to remove 80 % or reactant present in a gas stream by absorption in water. Find the volume of the tower for a countercurrent operation by straight mass transfer.

Given the following data:

F_g = 9000 mol/h at $\pi = 10^5$ Pa

P_A = 1000 Pa, p_{Aout} = 100 Pa

F_l = 90000 mpl/h, $k_{Ag}a$ = 0.36 mol /hm^3.Pa

$k_{Al}a$ = 72/h, C_T = 50000 mol/h

H_A = 2.0 Pa m^3/mol, k = 0 m^3/mol h [9]

(c) By means of diagrams, illustrate the following types of contactors:

(i) *irrigated bed counter current is tower*

(ii*) staged bubble tower counter current tower*. [4]

(d) (i) State the three rate controlling mechanisms of the shrinking core model for fluid -particle reaction [3]

(e) Spherical solid particles containing B are roasted isothermally in an oven with gas of constant composition. Solids are converted to a firm nonflaking product according to the SCM as follows: From the following conversion data (by chemical analysis) or core size data (by slicing and measuring) determine the rate controlling mechanism for the transformation of solids [6]

d_p	X_B	t, min
2	0.875	1
1	1	1

END OF EXAM

TABLE OF FORMULAE

Fluid fluid reactions

Fluid-fluid overall reaction equation:

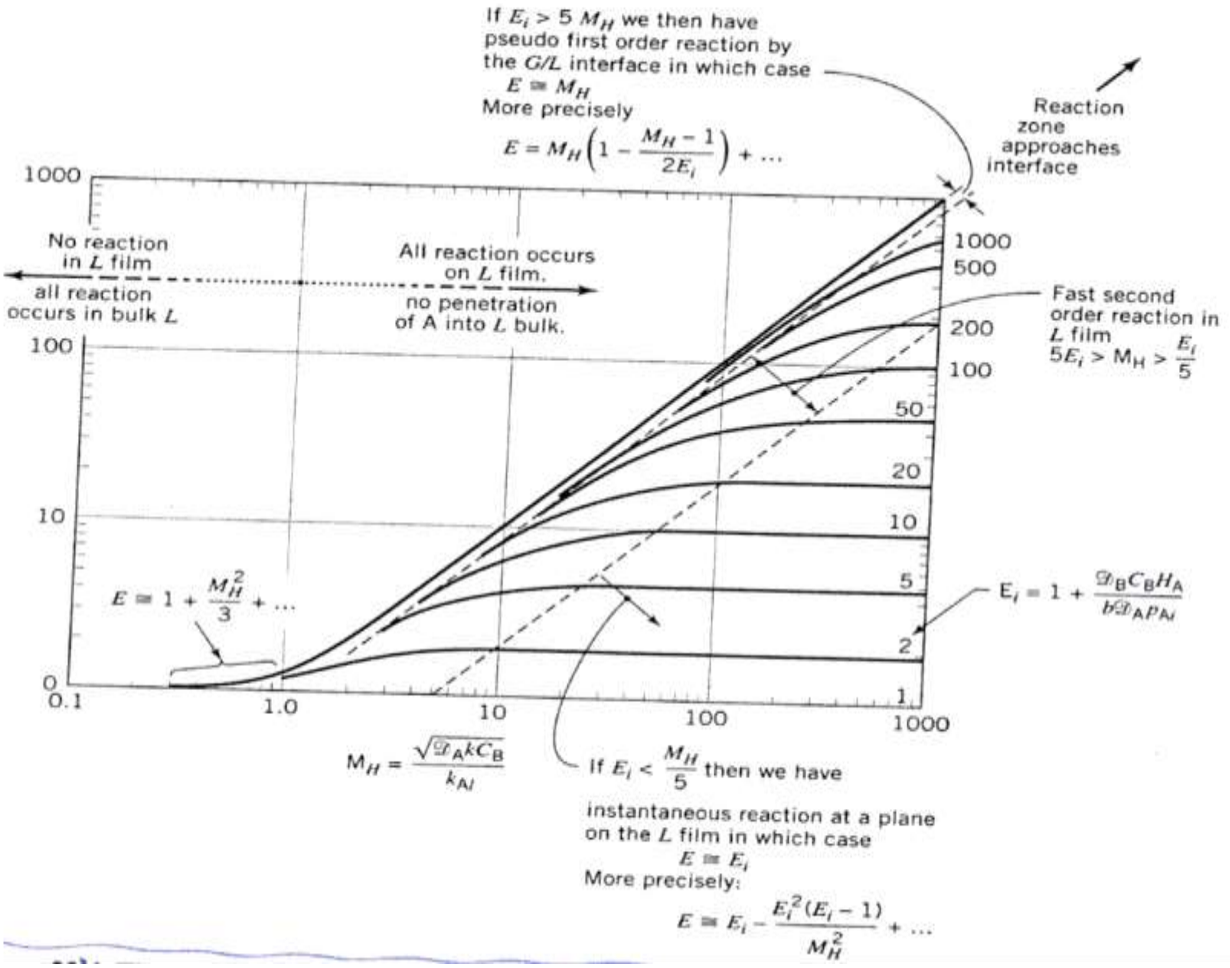
$$-r_A'''' = \frac{1}{\underbrace{\frac{1}{k_{Ag}a}}_{\substack{\text{gas film}\\\text{resistance}}} + \underbrace{\frac{H_A}{k_{Al}aE}}_{\substack{\text{liquid film}\\\text{resistance}}} + \underbrace{\frac{H_A}{kC_Bf_l}}_{\substack{\text{liquid bulk}\\\text{resistance}}}} p_A$$

Fluid-fluid overall reaction equation for different cases:

Case	**Formula of rate equation**
A and B	$\left(k_{Ag}p_A \le \frac{k_{Bl}C_B}{b}\right) \quad -r_A'' = -\frac{1}{S}\frac{dN_A}{dt} = k_{Ag}p_A$ **Case A: if $k_{Ag}P_A \ge \frac{k_{Bl}\ C_B}{b}$** **Case B: if $k_{Ag}P_A \le \frac{k_{Bl}\ C_B}{b}$**
C	$-r_A'''' = \frac{1}{\frac{1}{k_{Ag}a} + \frac{H_A}{k_{Al}aE}} p_A$

D	$-r''''_{\mathrm{A}} = \dfrac{1}{\dfrac{1}{k_{\mathrm{A}g}a} + \dfrac{H_{\mathrm{A}}}{a\sqrt{\mathscr{D}_{\mathrm{A}}kC_{\mathrm{B}}}}} p_{\mathrm{A}}$
E and F	$-r''''_{\mathrm{A}} = \dfrac{1}{\underbrace{\dfrac{1}{k_{\mathrm{A}g}a}}_{\substack{\text{gas film}\\ \text{resistance}}} + \underbrace{\dfrac{H_{\mathrm{A}}}{k_{\mathrm{A}l}aE}}_{\substack{\text{liquid film}\\ \text{resistance}}} + \underbrace{\dfrac{H_{\mathrm{A}}}{kC_{\mathrm{B}}f_l}}_{\substack{\text{liquid bulk}\\ \text{resistance}}}} p_{\mathrm{A}}$
G	$-r''''_{\mathrm{A}} = \dfrac{1}{\dfrac{1}{k_{\mathrm{A}g}a} + \dfrac{H_{\mathrm{A}}}{k_{\mathrm{A}l}a} + \dfrac{H_{\mathrm{A}}}{kC_{\mathrm{B}}f_l}} p_{\mathrm{A}}$
H	$-r''''_{\mathrm{A}} = \dfrac{kf_l}{H_{\mathrm{A}}} p_{\mathrm{A}}C_{\mathrm{B}} = kf_lC_{\mathrm{A}}C_{\mathrm{B}}$

Enhancement factor for fluid-fluid reactions as a function of M_H and E_i :



Fluid-fluid reactor design:

For any two points in an absorber:

$$p_{A2} - p_{A1} = \frac{F_l \pi}{F_g C_T}(C_{A2} - C_{A1})$$

Volume of a contractor:

$$V_r = hA_{cs} = \frac{F_g}{\pi}\int_{p_{A1}}^{p_{A2}} \frac{dp_A}{-r_A''''} = \frac{F_l}{C_T}\int_{C_{A1}}^{C_{A2}} \frac{dC_A}{-r_A''''}$$

$$= \frac{F_g}{\pi K_{Ag} a}\int_{p_{A1}}^{p_{A2}} \frac{dp_A}{p_A - p_A^*} = \frac{F_l}{C_T K_{Al} a}\int_{C_{A1}}^{C_{A2}} \frac{dC_A}{C_A^* - C_A}$$

coefficient on gas basis

$$\frac{1}{K_{Ag}} = \frac{1}{k_{Ag}} + \frac{H_A}{k_{Al}}$$

gas in equilibrium with liquid C_A, or

$$p_A^* = H_A C_A$$

coefficient on liquid basis

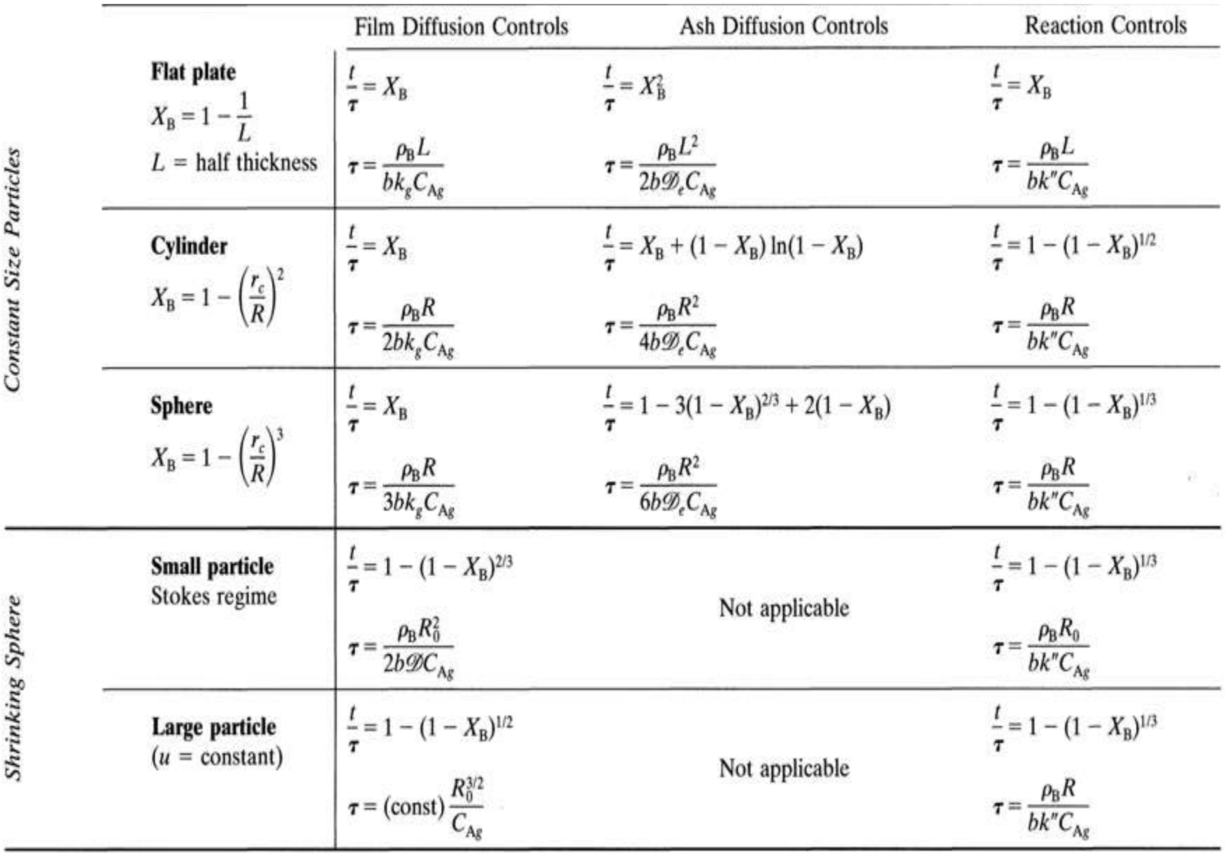
$$\frac{1}{K_{Al}} = \frac{1}{H_A k_{Ag}} + \frac{1}{k_{Al}}$$

liquid in equilibrium with gas p_A, or

$$C_A^* = p_A / H_A$$

Fluid-particle reactor design:

Conversions-Time Expressions for Various Shapes of Particles, Shrinking core model:



		Film Diffusion Controls	Ash Diffusion Controls	Reaction Controls
Constant Size Particles	**Flat plate** $X_B = 1 - \frac{1}{L}$ L = half thickness	$\frac{t}{\tau} = X_B$ $\tau = \frac{\rho_B L}{b k_g C_{Ag}}$	$\frac{t}{\tau} = X_B^2$ $\tau = \frac{\rho_B L^2}{2b\mathscr{D}_e C_{Ag}}$	$\frac{t}{\tau} = X_B$ $\tau = \frac{\rho_B L}{b k'' C_{Ag}}$
	Cylinder $X_B = 1 - \left(\frac{r_c}{R}\right)^2$	$\frac{t}{\tau} = X_B$ $\tau = \frac{\rho_B R}{2b k_g C_{Ag}}$	$\frac{t}{\tau} = X_B + (1 - X_B)\ln(1 - X_B)$ $\tau = \frac{\rho_B R^2}{4b\mathscr{D}_e C_{Ag}}$	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/2}$ $\tau = \frac{\rho_B R}{b k'' C_{Ag}}$
	Sphere $X_B = 1 - \left(\frac{r_c}{R}\right)^3$	$\frac{t}{\tau} = X_B$ $\tau = \frac{\rho_B R}{3b k_g C_{Ag}}$	$\frac{t}{\tau} = 1 - 3(1 - X_B)^{2/3} + 2(1 - X_B)$ $\tau = \frac{\rho_B R^2}{6b\mathscr{D}_e C_{Ag}}$	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/3}$ $\tau = \frac{\rho_B R}{b k'' C_{Ag}}$
Shrinking Sphere	**Small particle** Stokes regime	$\frac{t}{\tau} = 1 - (1 - X_B)^{2/3}$ $\tau = \frac{\rho_B R_0^2}{2b\mathscr{D} C_{Ag}}$	Not applicable	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/3}$ $\tau = \frac{\rho_B R_0}{b k'' C_{Ag}}$
	Large particle (u = constant)	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/2}$ $\tau = (\text{const}) \frac{R_0^{3/2}}{C_{Ag}}$	Not applicable	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/3}$ $\tau = \frac{\rho_B R}{b k'' C_{Ag}}$

Mean conversion of the solids leaving a plug flow reactor:

$$1 - \overline{X}_B = \sum_{R(t_p=\tau)}^{R_m} [1 - X_B(R_i)] \frac{F(R_i)}{F}$$

Chemical reaction controls:

$$[1 - X_B(R_i)] = \left(1 - \frac{t_p}{\tau(R_i)}\right)^3$$