

Interfacial Reactions

(Part I)

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7.1.1 Introduction

- ◆ Many reactions carried out in chemical industries involve a solid catalyst. In these heterogeneous systems, the reaction occurs at some of the catalytic sites, which are generally located on the external surface of the catalyst pellet and inside the pores of the pellet.
- ◆ The reactants have to be transported to these sites for the reaction to take place. The mass transfer to the catalyst surface may influence the overall rate of conversion by a significant extent.
- ◆ The important aspect to study is the interplay between the true chemical rate of reaction and the physical transport phenomena to obtain the overall conversion rate.
- ◆ Consider a porous catalyst particle around which a fluid is flowing containing the reactants. The general case of the reaction at the surface of a catalyst can be described by the steps given below.

Step 1: Transport of the reactants from the bulk fluid to the external surface of the catalyst particle

Step 2: Transport of the reactants by a diffusional process through the pores into the catalyst particle

Step 3: Adsorption of reactants on the internal and external catalyst sites

Step 4: Chemical reaction in the adsorbed state

Step 5: Desorption of the adsorbed products

Step 6: Transport of products by a diffusional process through the pores to the outer surface of the catalyst particle

Step 7: Transport of products from the external surface into the main flow

- ◆ If the particle is non-porous then the Steps 2 and 6 do not occur. The Steps 1 and 2 are schematically illustrated in Fig. 7.1.1.

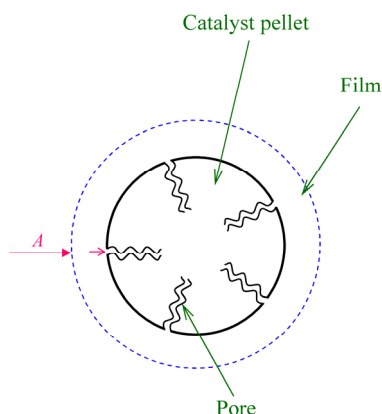


Fig. 7.1.1 Transport of reactant from the bulk to the interior of a catalyst particle.

- ◆ The best use of a porous catalyst is made when most of the internal surface area is readily accessible to the reactants. One of the ways this can be achieved is by using a small particle of high porosity.
- ◆ The modern industrial catalysts usually have a high surface area ($\sim 1 \times 10^6 \text{ m}^2/\text{kg}$). The micrograph of such a catalyst is shown in Fig. 7.1.2.

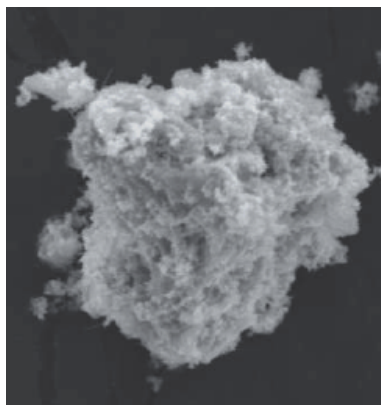


Fig. 7.1.2 A porous catalyst $\text{La}_{0.8}\text{K}_{0.2}\text{Cu}_{0.05}\text{Mn}_{0.95}\text{O}_3$ for the removal of nitrogen oxides and diesel soot [Peng et al. (2007); reproduced by permission from Elsevier Ltd., © 2007].

- ◆ If the chemical reaction is very fast in comparison with the mass transport, the reaction occurs in the outer part of the particle. In an extreme situation, only the external surface of the catalyst particle may be used in the reaction and the internal surface does not play any role.

- ◆ Agglomeration of the porous catalyst particles gives a pellet containing two void regions: small void spaces within the individual particles, and larger spaces between the particles. Such materials contain *bidisperse pore system*. The void spaces within the particles are called *microporous regions* and the void regions between particles are called *macroporous regions*.
- ◆ As per the IUPAC classification of pores by size, pores having diameter less than 2 nm are called *micropores* and the pores which have diameters greater than 50 nm are called *macropores*. The pores having diameters between 2 nm and 50 nm are called *mesopores*.
- ◆ Typical microporous materials are zeolites. Examples of mesoporous solids are silicas and modified layered materials.
- ◆ Mesoporous solids can be prepared by various methods, which will be discussed in Module 9. One of the methods is templating by liquid crystals, followed by calcination.

7.1.2 Langmuir–Hinshelwood model

- ◆ A well known approach to describe the kinetics of gas–solid reactions was proposed by C. N. Hinshelwood (1940) based on Langmuir’s theory of chemisorption (see Lecture 4 of Module 4).
- ◆ Let us consider the situation where one reactant molecule occupies a single site (S) on the surface of the catalyst. The adsorption process is represented by,



- ◆ Let us represent the concentration of reactant A in the gas phase as c_A (mol/m³) and the adsorbed concentration of A on the catalyst surface as $\hat{c}_A$ (expressed as mol/kg of catalyst). The net rate of adsorption of A is given by,

$$r_a = k_a c_A (\hat{c}_t - \hat{c}_A) - k'_a \hat{c}_A \quad (7.1.2)$$

where $\hat{c}_t$ is the concentration corresponding to a complete monolayer on the catalyst (expressed as mol/kg of catalyst). The first term on the right side of Eq.

(7.1.2) is valid if only the reactant A in the gaseous feed adsorbs on the surface of the catalyst.

- ◆ The quantity, $(\hat{c}_t - \hat{c}_A)$, represents the concentration corresponding to the vacant sites, $\hat{c}_v$. The adsorption equilibrium constant for A is given by $K_a^A = k_a/k'_a$. Therefore,

$$r_a = k_a \left(c_A \hat{c}_v - \frac{1}{K_a^A} \hat{c}_A \right) \quad (7.1.3)$$

- ◆ If the rate of adsorption is much faster than the other steps in the overall conversion process, the concentration of A on the catalyst surface will be in equilibrium with the concentration of A in the gas phase. The equilibrium concentration of A is obtained by setting $r_a = 0$, which gives,

$$\hat{c}_{A,\text{eq}} = K_a^A c_A \hat{c}_v \quad (7.1.4)$$

Example 7.1.1: A feed contains a diatomic gas along with an inert gas which does not adsorb on the catalyst. The diatomic gas dissociates upon adsorption and each atom occupies one adsorption site. Derive the expression for the equilibrium concentration of atomically adsorbed A assuming that the rate of adsorption is much faster than the other steps.

Solution: The adsorption of the gas can be represented as,



The net rate of adsorption is given by,

$$r_a = k_a \left(c_{A_2} \hat{c}_v^2 - \frac{1}{K_a^{A_2}} \hat{c}_A^2 \right) \quad (\text{ii})$$

Since the inert gas does not adsorb, A_2 is the only adsorbable gas. Therefore, site balance gives,

$$\hat{c}_v = \hat{c}_t - \hat{c}_A \quad (\text{iii})$$

Substituting $\hat{c}_v$ from Eq. (iii) into Eq. (ii) and setting $r_a = 0$ we get,

$$c_{A_2} (\hat{c}_t - \hat{c}_{A,\text{eq}})^2 = \frac{1}{K_a^{A_2}} \hat{c}_{A,\text{eq}}^2 \quad (\text{iv})$$

Simplifying eq. (iv) we get,

$$\hat{c}_{A,\text{eq}} = \frac{\hat{c}_t \left(K_a^{A_2} c_{A_2} \right)^{1/2}}{1 + \left(K_a^{A_2} c_{A_2} \right)^{1/2}} \quad (\text{v})$$

- ◆ Let us now consider the surface reaction step with the reaction expressed as: $A + B \rightleftharpoons C$. The reaction may occur with both A and B adsorbed on the catalyst surface or one of the reactants adsorbed on the catalyst site and the other reactant present in the gas phase, as shown in Fig. 7.1.3.

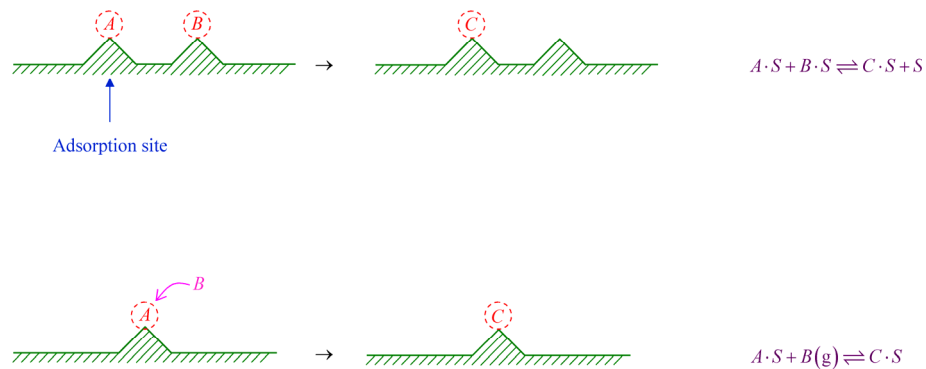


Fig. 7.1.3 Surface reaction involving both adsorbed A and adsorbed B on the adjacent sites, and adsorbed A and non-adsorbed B .

- ◆ Let us consider the first case, which can be expressed as,



Only those A and B molecules will react which are adsorbed on adjacent sites.

- ◆ The rate of forward reaction should be proportional to the concentration of the pairs of adjacent sites occupied by A and B molecules, assuming that the rate of forward reaction is first-order in both A and B on the catalyst surface.
- ◆ The concentration of these pairs is approximately equal to $\hat{c}_A \hat{c}_B / \hat{c}_t$ (which is valid if the fraction of the surface occupied by the A molecules is small).

$$r_1 = k_s \hat{c}_A \hat{c}_B / \hat{c}_t \quad (7.1.6)$$

- ◆ The rate of the reverse reaction is given by,

$$r_2 = k'_s \hat{c}_C \hat{c}_v / \hat{c}_t \quad (7.1.7)$$

Therefore, the net rate of surface reaction is,

$$r_s = (k_s \hat{c}_A \hat{c}_B - k'_s \hat{c}_C \hat{c}_v) / \hat{c}_t = k_s (\hat{c}_A \hat{c}_B - \hat{c}_C \hat{c}_v / K_s) / \hat{c}_t \quad (7.1.8)$$

where $K_s (\equiv k_s / k'_s)$ is the equilibrium constant for the surface reaction.

- ◆ If the surface reaction step is intrinsically fast with respect to the other steps, the process would occur at equilibrium. Setting $r_s = 0$, we obtain,

$$K_s = \left[\frac{\hat{c}_v \hat{c}_C}{\hat{c}_A \hat{c}_B} \right]_{\text{eq}} \quad (7.1.9)$$

- ◆ In the second case, only the reactant A is adsorbed and the reactant B is present in the gas phase. We can represent the reaction as,



- ◆ The net rate of surface reaction for this mechanism is given by,

$$r_s = k_{s1} \hat{c}_A c_B - k'_{s1} \hat{c}_C = k_{s1} (\hat{c}_A c_B - \hat{c}_C / K'_s) \quad (7.1.11)$$

At equilibrium, $r_s = 0$,

$$K'_s = \left[\frac{\hat{c}_C}{\hat{c}_A c_B} \right]_{\text{eq}} \quad (7.1.12)$$

- ◆ For the desorption of the product, C , the mechanism may be expressed as,



The rate of desorption is given by,

$$r_d = k'_d \hat{c}_C - k_d c_C \hat{c}_v = -k_d \left(c_C \hat{c}_v - \hat{c}_C / K_d^C \right) \quad (7.1.14)$$

- ◆ If the rate of desorption is faster with respect to the adsorption and surface reaction steps, the equilibrium concentration of C is given by,

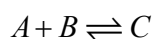
$$\hat{c}_{C,\text{eq}} = K_d^C c_C \hat{c}_v \quad (7.1.15)$$

- ◆ At steady state, the rates of adsorption, surface reaction and desorption are equal.
- ◆ The rate equations written above contain adsorbed concentrations of the reactants, products and the vacant sites (i.e., $\hat{c}_A$, $\hat{c}_B$, $\hat{c}_C$ and $\hat{c}_v$). To determine the rates

from the concentrations in the gas phase, these quantities need to be eliminated. A simple procedure is to assume that one of the steps controls the rate. The other two steps occur at near-equilibrium conditions. This simplifies the rate expressions and reduces the number of rate and equilibrium constants that must be determined from experiment. This is also valid from a practical point of view since in many cases it has been observed that only one of the steps controls the overall catalytic reaction.

- ◆ Let us consider the reaction scheme presented in Table 7.1.1, and follow the procedure discussed above.

Table 7.1.1 Adsorption, surface reaction and desorption schemes for the reaction:



Step	Mechanism
Adsorption	$A + S \rightleftharpoons A \cdot S$
	$B + S \rightleftharpoons B \cdot S$
Surface reaction	$A \cdot S + B \cdot S \rightleftharpoons C \cdot S + S$
Desorption	$C \cdot S \rightleftharpoons C + S$

- ◆ Consider that surface reaction is the rate-controlling step. Then $\hat{c}_A$, $\hat{c}_B$ and $\hat{c}_C$ are the equilibrium values corresponding to the adsorption and desorption steps. From Eq. (7.1.4) we can write,

$$\hat{c}_{B,\text{eq}} = K_a^B c_B \hat{c}_v \quad (7.1.16)$$

From Eq. (7.1.8), we get,

$$\text{rate} = r_s = \frac{k_s}{\hat{c}_t} \left[K_a^A K_a^B c_A c_B \hat{c}_v^2 - \frac{K_d^C}{K_s} c_C \hat{c}_v^2 \right] \quad (7.1.17)$$

- ◆ We can write a site-balance, in which $\hat{c}_t$ is given by,

$$\hat{c}_t = \hat{c}_v + \hat{c}_{A,\text{eq}} + \hat{c}_{B,\text{eq}} + \hat{c}_{C,\text{eq}} \quad (7.1.18)$$

Therefore, from Eqs. (7.1.4), (7.1.15), (7.1.16) and (7.1.18) we get,

$$\hat{c}_v = \frac{\hat{c}_t}{1 + K_a^A c_A + K_a^B c_B + K_d^C c_C} \quad (7.1.19)$$

- ◆ Now, substituting the value of $\hat{c}_v$ from Eq. (7.1.19) into Eq. (7.1.17), we obtain,

$$\text{rate} = k_s \hat{c}_t \frac{K_a^A K_a^B c_A c_B - K_d^C c_C / K_s}{\left(1 + K_a^A c_A + K_a^B c_B + K_d^C c_C\right)^2} \quad (7.1.20)$$

- ◆ Several simplifications of Eq. (7.1.20) can be made depending on the characteristics of the steps given in Table 7.1.1. For example, if the adsorption of all the components is weak, the denominator of Eq. (7.1.20) approaches unity, and the rate equation becomes,

$$\text{rate} = k_s \hat{c}_t \left[K_a^A K_a^B c_A c_B - K_d^C c_C / K_s \right] \quad (7.1.21)$$

- ◆ Rate expressions for the situations where either adsorption or desorption is the controlling step can be derived easily following a procedure similar to that described above.
- ◆ If the desorption of product, C, controls the whole reaction, it can be shown that the rate expression is given by,

$$\text{rate} = k_d \hat{c}_t \left(\frac{K_a^A K_a^B K_s}{K_d^C} \right) \left[\frac{c_A c_B - \left(\frac{K_d^C}{K_a^A K_a^B K_s} \right) c_C}{1 + K_a^A c_A + K_a^B c_B + K_a^A K_a^B K_s c_A c_B} \right] \quad (7.1.22)$$

7.1.3 External transport processes

- ◆ The first step in a heterogeneous catalytic reaction is the transport of the reactants from the bulk of the fluid to the surface of the catalyst. The concentration difference between the bulk and the surface is the driving force for this transport. The concentration of the reactants at the surface of the catalyst is lower than that in the bulk of the fluid.
- ◆ The difference in concentration of a reactant between the bulk and the surface depends upon several factors such as the velocity pattern of the fluid near the

surface, the physical properties of the fluid and the rate of chemical reaction. All these factors are expressed in terms of the mass transfer coefficient and the reaction rate constant. For those reactions in which significant thermal effects are involved, temperature difference between the bulk and the surface is developed. The temperature difference between the bulk and the surface depends upon the nature of the reaction (i.e., whether it is endothermic or exothermic). The effect of temperature difference on mass transfer can be significant.

- ◆ Let us consider a first-order irreversible gaseous reaction: $A \rightarrow B$ on a solid catalyst pellet. At steady state, the rate of transport of A from the bulk fluid to the gas–solid interface is equal to the rate of reaction at the catalyst surface. The rate of mass transfer from the bulk to the catalyst surface is given by,

$$r_p = k_m a_m (c_A^b - c_A^s) \quad (7.1.23)$$

where k_m is the mass transfer coefficient between the bulk and the solid surface based on a unit external area of the catalyst particle, a_m is the external surface area of the pellet per unit mass, c_A^b is the concentration of A in the bulk gas and c_A^s is the concentration of A at the surface.

- ◆ Since the reaction is of first-order, the rate is given by,

$$r_p = k c_A^s \quad (7.1.24)$$

where k is the reaction rate constant based on the unit mass of the catalyst. Therefore, c_A^s and c_A^b are related as,

$$c_A^s = \left(\frac{k_m a_m}{k + k_m a_m} \right) c_A^b \quad (7.1.25)$$

- ◆ From Eqs. (7.1.24) and (7.1.25), we can express the rate as,

$$r_p = \left(\frac{k k_m a_m}{k + k_m a_m} \right) c_A^b = \frac{c_A^b}{1/(k_m a_m) + 1/k} \quad (7.1.26)$$

- ◆ The rate expressed by Eq. (7.1.26) is an example of *global rate* because it includes the external mass transfer effects and expresses the rate of reaction in terms of the reactant concentration in the bulk phase. However, it is a very

simplified global rate expression because it does not consider the heat transfer and internal mass transfer effects.

- ◆ The two terms in the denominator of Eq. (7.1.26), viz. $1/k$ and $1/(k_m a_m)$, represent the reaction and mass transfer resistances, respectively. If the rate of reaction is much faster than the rate of mass transfer, c_A^s approaches zero. On the other hand, if the mass transfer rate is much higher than the rate of reaction, c_A^s approaches c_A^b . These two limiting cases are schematically shown in Fig. 7.1.4.

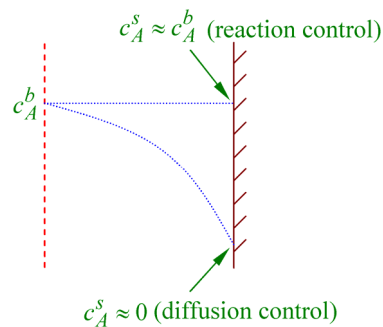


Fig. 7.1.4 Mass transport from bulk of fluid to the surface of catalyst under reaction control and diffusion control.

- ◆ The heat evolved by chemical reaction is given by,

$$Q_R = (-\Delta H) r_p = (-\Delta H) k_0 \exp\left(-\frac{E}{RT_s}\right) c_A^s \quad (7.1.27)$$

where k_0 is the pre-exponential factor, E is the activation energy and R is the gas constant.

- ◆ In Eq. (7.1.27), it has been assumed that the reaction rate constant, k , varies with temperature following the Arrhenius equation. The rate of heat loss from the catalyst surface (expressed per unit mass) is given by,

$$Q_L = h a_m (T_s - T_b) \quad (7.1.28)$$

where h is the heat transfer coefficient.

- ◆ At steady state, the heat evolved by the reaction, Q_R , is equal to the heat lost from the catalyst, Q_L . Therefore, from Eqs. (7.1.27) and (7.1.28) we get,

$$T_s - T_b = \frac{(-\Delta H) k_0 \exp\left(-\frac{E}{RT_s}\right) c_A^s}{h a_m} \quad (7.1.29)$$

- ◆ From Eqs. (7.1.28) and (7.1.29) we get,

$$c_A^b - c_A^s = \frac{k c_A^s}{k_m a_m} = \frac{k_0 \exp\left(-\frac{E}{RT_s}\right) c_A^s}{k_m a_m} \quad (7.1.30)$$

- ◆ If ΔH , k_0 , E , h , k_m , a_m , c_A^b and T_b are known, we can determine c_A^s and T_s by solving Eqs. (7.1.29) and (7.1.30) simultaneously.

7.1.3.1 Determination of mass and heat transfer coefficients

- ◆ The mass transfer coefficient between the bulk fluid and the surface of the particle can be obtained from the correlations given in the literature. Many such correlations are expressed in terms of the j -factor, which is defined as,

$$j_D = \left(\frac{k_m \rho}{G}\right) \left(\frac{a_m}{a_t}\right) \left(\frac{\mu}{\rho D}\right)^{2/3} \quad (7.1.31)$$

where G is the superficial mass velocity based on the cross-sectional area of the empty reactor, ρ is the density of the fluid, D is the diffusivity of the component being transferred, μ is the viscosity of the fluid, and a_t is the total external area of the particles.

- ◆ The ratio, a_m/a_t , allows for the possibility that the effective mass transfer area, a_m , may be less than the total external area, a_t . The following equation (Dwivedi and Upadhyay, 1977) can be used for calculating the mass transfer coefficient in fixed beds.

$$j_D = \frac{0.4548}{\varepsilon_b} \left(\frac{d_p G}{\mu}\right)^{-0.407}, \quad d_p G / \mu > 10 \quad (7.1.32)$$

where ε_b represents the void fraction of the bed.

- ◆ The j -factor for heat transfer is defined as,

$$j_H = \left(\frac{h}{c_p G} \right) \left(\frac{a_m}{a_t} \right) \left(\frac{c_p \mu}{k_t} \right)^{2/3} \quad (7.1.33)$$

where c_p is the heat capacity and k_t is the thermal conductivity of the fluid.

- ♦ Example 7.1.2 illustrates the calculation of mass transfer coefficient.

Example 7.1.2: A gaseous feed of sulfur dioxide in air is passed through a packed bed of spherical catalyst pellets ($d_p = 1.8$ mm) at 300 K. The velocity of the gas is 15 cm/s, diffusivity of SO₂ is 1.6×10^{-5} m²/s, density of the gas is 1.8 kg/m³ and the viscosity is 16×10^{-6} Pa s. The void fraction of the bed is 0.6 and the effective mass transfer area is 70% of the total external area of the pellets. Calculate the mass transfer coefficient.

Solution: The Reynolds number is,

$$\text{Re} = \frac{d_p G}{\mu} = \frac{d_p v \rho}{\mu} = \frac{1.8 \times 10^{-3} \times 0.15 \times 1.8}{16 \times 10^{-6}} = 30.375$$

$$\varepsilon_b = 0.6$$

$$\therefore j_D = \frac{0.4548}{\varepsilon_b} (\text{Re})^{-0.407} = \left(\frac{0.4548}{0.6} \right) (30.375)^{-0.407} = 0.189$$

$$\text{Now, } \frac{\mu}{\rho D} = \frac{16 \times 10^{-6}}{1.8 \times 1.6 \times 10^{-5}} = 0.56$$

$$\text{Given, } \frac{a_m}{a_t} = 0.7$$

Therefore, from Eq. (7.1.31) we get,

$$0.189 = \left(\frac{k_m}{0.15} \right) (0.7) (0.56)^{2/3} = 3.1705 k_m$$

$$\therefore k_m = 0.06 \text{ m/s}$$

Exercise

Exercise 7.1.1: Derive the rate expression for the reaction: $A + B \rightleftharpoons C$, if the adsorption of the reactant A is the rate-controlling step. Assume that the reaction follows the mechanism described in Table 7.1.1.

Exercise 7.1.2: Derive eq. (7.1.22).

Exercise 7.1.3: For a gas–solid catalytic reaction, the reaction rate constant is $0.15 \text{ m}^3 (\text{kg catalyst})^{-1} \text{ s}^{-1}$. The external surface area per unit mass of the pellet is $125 \text{ m}^2/(\text{kg catalyst})$. The mass transfer coefficient is $2.6 \times 10^{-4} \text{ m/s}$. Determine whether diffusion or the kinetics of surface reaction control the overall process.

Exercise 7.1.4: In a packed bed filled-up with 2 mm diameter catalyst pellets, compute the j_D factor if a gas is flowing at a velocity of 22 cm/s. The density of the gas is 2 kg/m^3 and its viscosity is $1 \times 10^{-5} \text{ Pa s}$. The void fraction of the bed is 0.58.

Exercise 7.1.5: Consider the vapor phase dehydration of ethanol, given by the reaction: $2\text{C}_2\text{H}_5\text{OH} = \text{C}_2\text{H}_5\text{OC}_2\text{H}_5 + \text{H}_2\text{O}$. Kabel and Johanson (1962) have studied the application of Langmuir–Hinshelwood model for the aforesaid reaction carried out using a sulfonated copolymer of styrene and divinylbenzene as catalyst. If surface reaction is the rate-controlling step, the following rate equation is applicable when the reaction occurs between two adjacently adsorbed ethanol molecules.

$$\frac{\sqrt{r_0}}{p_{A0}} = \frac{\sqrt{\bar{k}}}{1 + K_E} - \sqrt{r_0} \left(\frac{K_A - K_E}{1 + K_E} \right)$$

where r_0 is the initial reaction rate, p_{A0} is the partial pressure of alcohol in the feed, K_A and K_E are adsorption constants of alcohol and ether, respectively, and $\bar{k}$ is a constant. If the reaction occurs between an adsorbed ethanol molecule and a gaseous ethanol molecule, the rate equation is given by,

$$\frac{r_0}{p_{A0}^2} = \bar{k} - K_A \left(\frac{r_0}{p_{A0}} \right)$$

The initial rate data at 393 K are presented below.

p_{A0} (Pa)	r_0 , mol (kg catalyst) ⁻¹ s ⁻¹	p_{A0} (Pa)	r_0 , mol (kg catalyst) ⁻¹ s ⁻¹
4.772×10^4	1.447×10^{-3}	8.886×10^4	2.147×10^{-3}
5.796×10^4	1.672×10^{-3}	9.595×10^4	2.225×10^{-3}
6.495×10^4	1.780×10^{-3}	1.013×10^5	2.245×10^{-3}

Which mechanism among the two fits the experimental data?

Exercise 7.1.6: Answer the following questions clearly.

- 1) What is the difference between *bulk reaction* and *interfacial reaction*? Give three examples of interfacial reaction.
- 2) Mention the steps through which a catalytic reaction takes place.
- 3) What do you understand by *bidisperse pore system*?
- 4) What is the difference between a *micropore* and a *macropore*? What is a *mesopore*?
- 5) Discuss the salient features of Langmuir–Hinshelwood theory.
- 6) Draw the variation of concentration of reactant from the bulk phase to the surface of a catalyst if there is a high resistance for mass transport.
- 7) Draw the variation of temperature from the bulk phase to the surface of a catalyst for an exothermic reaction and an endothermic reaction.
- 8) Explain how the rate constant for surface reaction varies with temperature.
- 9) Explain how you will calculate the mass transfer coefficient for transport of reactant from the bulk phase to the surface of a catalyst.

Suggested reading

Textbooks

- ♦ J. M. Smith, *Chemical Engineering Kinetics*, McGraw-Hill, Singapore, 1981, Chapters 9 & 10.
- ♦ P. Ghosh, *Colloid and Interface Science*, PHI Learning, New Delhi, 2009, Chapter 12.

Reference books

- ♦ H. S. Fogler, *Elements of Chemical Reaction Engineering*, Prentice-Hall of India, New Delhi, 2008, Chapters 10 & 11.

Journal articles

- ♦ P. N. Dwivedi and S. N. Upadhyay, *Ind. Eng. Chem. Proc. Des. Dev.*, **16**, 157 (1977).
- ♦ R. L. Kabel and L. N. Johanson, *AIChE J.*, **8**, 621 (1962).
- ♦ X. Peng, H. Lin, W. Shangguan, and Z. Huang, *Catal. Commun.*, **8**, 157 (2007).