CHAPTER II

LITERATURE REVIEW

The rate of solid dissolution solid particle is controlled by the relative velocity of solid to liquid and the rate of renewal of liquid layer which may depend on the intensity of turbulence around the solid particles.

2.1 Rate of Solution of Solid Particles [21]

Rate of solution of solid particles is expressed as follows :

$$-\frac{dW}{Vdt} = K\frac{A}{V}(C_s - C) \quad \text{..... (2.1)}$$

where W : mass of solid particles [g]

V : volume of liquid [cm^3]

K : dissolution rate coefficient [cm/sec]

A : contact surface area of solid and liquid [cm^2]

C_s : saturated concentration [g/cm^3]

C : concentration at time t [g/cm^3]

Several procedures are presented to derive the rate of solution using Eq.(2.1).

A. Method presented by Hixson and Crowell

Hixson and Crowell integrated Eq.(2.1) substituting the following relations :

$$Kt = (V/\alpha_w m^{2/3}) \left\{ \frac{3^{0.5}\tan^{-1}(2\sqrt{3}m^{1/3}(W_o^{1/3}-W^{1/3}))}{3m^{2/3}+(2W_o^{1/3}-m^{1/3})(2W^{1/3}-m^{1/3})} + 1.1513\log\frac{(m^{1/3}+W_o^{1/3})^2}{(m^{1/3}+W^{1/3})^2} \right\} x \left\{ \frac{m^{2/3}-m^{1/3}W^{1/3}+W^{2/3}}{m^{2/3}-m^{1/3}W_o^{1/3}+W_o^{2/3}} \right\} \quad \text{.....(2.2)}$$

$A = \alpha_w W^{2/3}$ $C_s = W_s/V$

$C = (W_o - W)/V$ $m = W_s - W_o$

where α_w = Shape factor relating the surface area with mass
W_s = Mass needed to saturate the liquid [g]
W_o = Total mass charged [g]
K = Dissolution rate coefficient [cm/sec]
t = Time [sec]
W = Mass of solid particles [g]
V = Volume of liquid (cm^3)
A = Contact surface area of solid and liquid (cm^2)
C_s = Saturated concentration (g/cm^3)
C = Concentration at time t (g/cm^3)

where α_w is a shape factor relating the surface area with mass, W_S is the mass needed to saturate the liquid and W_O is the total mass charged. Eq.(2.2) shows the relation between the time t and the cube root of the weight of solid at that time and is called, "cube root law". In the range where the dissolution rate coefficient K and shape factor α_w are assumed constant, the rate of dissolution is obtained at any time and the value K is determined when the value α_w or A is given.

B. Method presented by Wilhelm et al.

By using the following relations and notations,

$$W_d = W_o - W, \quad X = W_d/W_s, \quad Y = W_o/W_s$$
$$A = \alpha_v n^{1/3} W^{2/3}/\rho_s^{2/3}, V = (1+\alpha X)V_o, \quad V_s = (1+a)V_o$$

Eq.(2.1) is transformed to an integral form;

$$Z = \int_0^x \frac{dX}{(Y-X)^{2/3}\,(1/(1+\alpha)) - (X/(1+\alpha X))} = \frac{KA_s t}{V} \quad .....(2.3)$$

where α_w is a shape factor relating the surface area with volume of solid particle and V_o is the liquid volume at concentration zero. Liquid volume at an arbitrary saturation X is assumed to be $(1+aX)V_o$

By graphical integration, Eq.(2.3) is calculated and is used to evaluate K when the relation between Z and X is drawn on a graph using Y as a parameter. Wilhelm *et al.* showed a diagram for the system in the case of the dissolution of sodium chloride in water, is equal to 0.13. From the measurement of W_d at time t, the dissolution rate coefficient K is obtained. Compared with the method 1 proposed by Hixson where volumetric change was neglected, Wilhelm considered the change of liquid volume to be proportional to the ratio of saturation.

C. Graphical differentiation

In a range of small change in surface area and liquid concentration, the rate of solution is obtained by a graphical differentiation of concentration change with time at the beginning of dissolution.

$$-\left(\frac{dW}{Adt}\right)_{t=0} = KA_oC_s / V \qquad \text{.....(2.4)}$$

2.2 Rate of Dissolution of Solid in Baffled Vessels

2.2.1 Humphrey and Van Ness's Correlation [7]

Humphrey and Van Ness measured the rate of solution of $Na_2S_2O_3.5H_2O$ crystals suspended in a flow type agitation vessel. They used a baffled vessel of 1 *ft* diameter agitated by a 3-bladed marine propeller and 6-bladed turbine of $d/D = 1/3$. The correlation of the mass transfer coefficients is the Eq.(2.5) and the numerical values of c, p and q are as follows;

For propeller $c = 0.47, p = 0.58, q = 0.5$ $63{,}000 < Re < 330{,}000$

For turbine $c = 0.022, p = 0.87, q = 0.5$ $31{,}000 < Re < 89{,}000$

In the range of particle diameter 4 ~ 12 mesh, no a significant effect was observed by the change of particle size.

$$KD/D_f = D/X = c\,[D^2 n\rho/\mu]^p\,[\rho\mu/D_f]^q \quad \text{.....(2.5)}$$

$$Sh = c\,Re^a\,Sc^b \quad \text{.....(2.5)'}$$

2.2.2 Barker and Treybal's Correlation. [3]

Barker and Treybal studied the rate of solution of solid particles suspended in water and 45% sucrose solution in 2 - 12 in baffled vessels agitated by a six-flat-blade turbine. The disssolution rate coefficients of boric acid, rock salt and benzoic acid in several sizes were correlated by the following equation.

$$ln(10k) = I + 0.85\,V^{0.02875}\,ln(Re/10^4) \quad \text{.....(2.6)}$$

where k is the mass transfer coefficient in [ft/hr], Re ($\pi d^2 n/\nu$) is the modified Reynolds number, V is the liquid volume[ft^3] and I is a function of V. By taking 0.833 as an average value or $0.85V^{0.02875}$, the following dimensionless equation is obtained.

$$(KD/D_f) = 0.02(Re)^{0.833}\,(Sc)^{0.5} \quad \text{.....(2.7)}$$

Treybal *et al.* proposed a constant value of 0.833 for the Reynolds index. However, according to the study of the author, Reynolds index is larger for particles of larger density as shown in Fig. 2.1 in baffled vessels. Therefore, the constant value, 0.833 obtained by Treybal *et al.* may be due to a narrow-range of density difference.

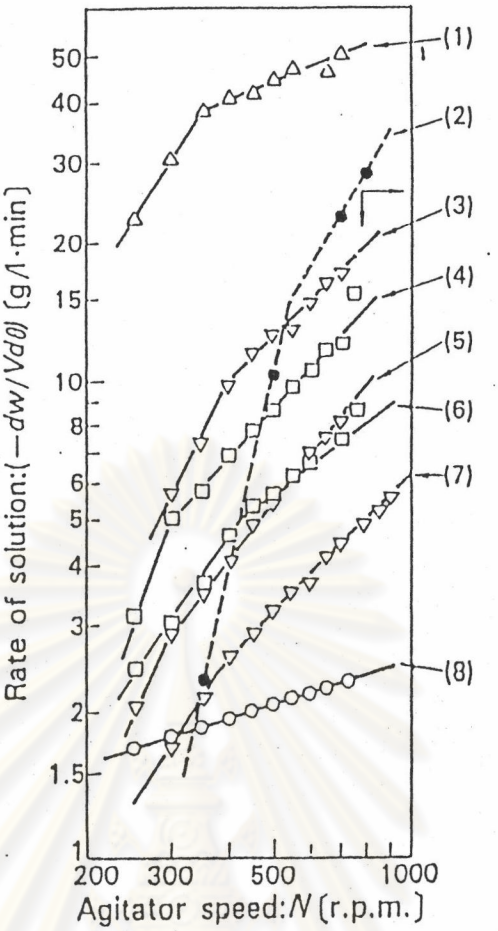

Figure 2.1 Effect of impeller speed on the rate of solution in baffled vessels.[21]

(1) $CO(NH_2)_2$, 12~14#, $\rho_S = 1.26$

(2) Zn-HCI, 80~100#, $\rho_S = 6.95$

(3) $K2Cr_2O_7$, 28~45#, $\rho_S = 2.63$

(4) NaCl (rock salt), 20~28#, $\rho_S = 2.17$

(5) $K2Cr_2O_7$, 20~28#, $\rho_S = 2.63$

(6) NaCl (spherical), 10~12#, $\rho_S = 2.10$

(7) $K_2Cr_2O_7$, 12~16#, $\rho_S = 2.63$

(8) Crotonic acid, 20~28#, $\rho_S = 1.16$

2.2.3 Johnson and Chen-Jung Huang's Correlation.[8]

They undertook experiments on the dissolution of solids using a turbine with six straight blades as impeller.The vessel was equipped with four baffles, and they derived the equation.

$$KT/D_V = 0.0924 [D_i^2 N\rho_l / \mu]^{0.710} [\mu / \rho_l D_V]^{0.5} \quad .....(2.8)$$

2.3 Correlation of Dissolution Rate Coefficients with various Factors in Solid-liquid Agitation

2.3.1 Hixson and Baum's Correlation [1]

Hixson and Baum studied the rate of mass transfer from solid particles 0.25 cm in diameter in liquids agitated by a turbine and by a marine propeller in unbaffled vessels of various diameters and obtained a dimensionless equation.

$$KT/Dv = T/Z = r[T^2 N\rho_l / \mu]^p [\mu / \rho_l D_V]^q \quad .....(2.9)$$

$$Sh_T = r\, Re_a^p\, Sc^q \quad .....(2.10)$$

The experimental data are correlated in Figure 2.2(a) and 2.2 (b) and represented by the following equations :

For Turbine

$$Re_T < 6.7 \times 10^4 \; ; Sh_T = 2.7 \times 10^{-5} Re_T^{1.4} Sc^{0.5} \quad .....(2.11)$$

$$Re_T > 6.7 \times 10^4 \; ; Sh_T = 0.16\, Re_T^{0.63} Sc^{0.5} \quad .....(2.12)$$

For Marine Propeller

$$3{,}300 < Re_T < 330{,}000; \; Sh_T = 3.5 \times 10^{-4} Re_T^{1.0} Sc^{0.5} \quad .....(2.13)$$

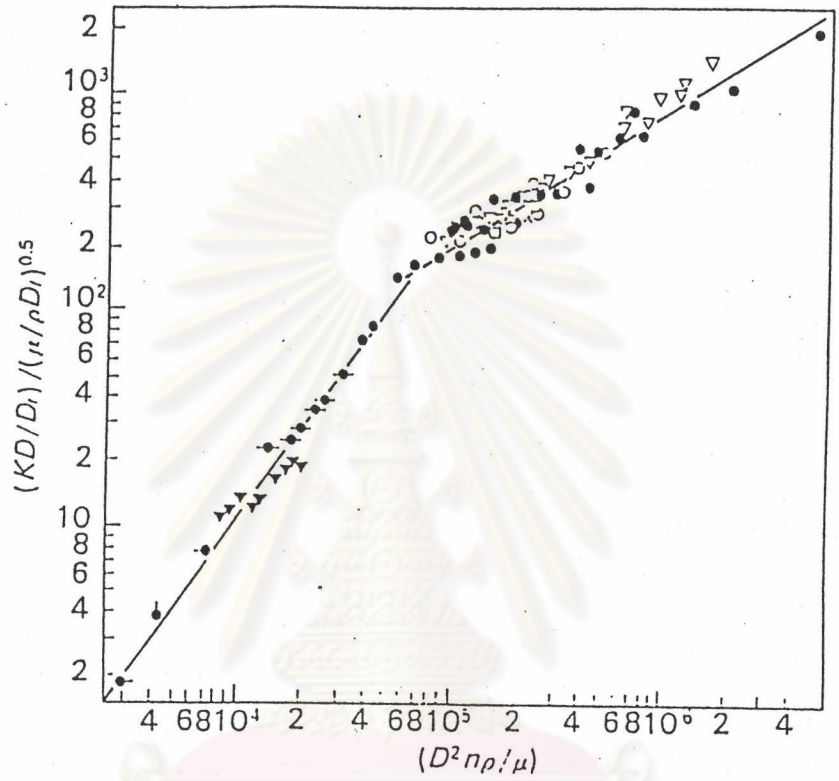

Figure 2.2(a) : Correlation of mass transfer coefficients. [21]

● : Benzoic acid-water, ○ : Benzoic acid-benzene,

-● : Benzoic acid-sperm oil, ● : Benzoic acid cotton seed oil,

●- : Benzoic acid-rapeseed oil, -●- : Benzoic acid-40% sucrose,

▼ : Benzoic acid-ethylene glycol, ▽ : Barium chloride-water,

□ : Rock salt-water, × : Naphthalene-methanol

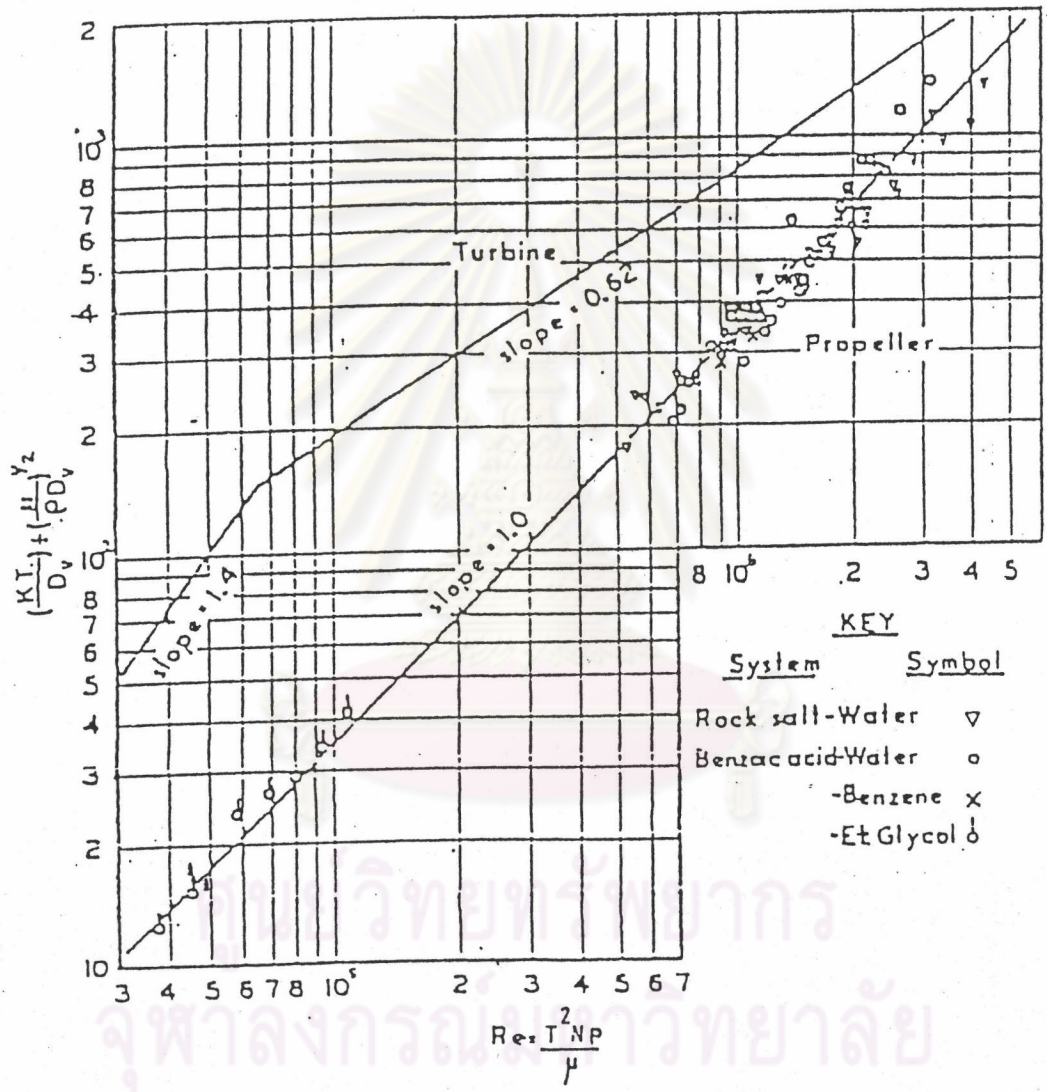

Figure 2.2(b) : Graphical determination of constant exponents of general equation for mass transfer.[21]

2.3.2 Nagata's Correlation [2]

More general correlation for geometrically similar, unbaffled vessels, with spherical and granular solids is

$$kT/D_v = 3.60x10^{12}(T^2N\rho_l/\mu)^p\ (\rho_l D_v)^q\ (D^2_v/T^3g)^{0.627}$$
$$(d_p/T)^{3.08}(\Delta\rho/\rho_l)^{-2.82} \qquad \text{.....(2.14)}$$

$$where: p=0.0802(T^3g\rho_l^2/\mu^2)^{0.0772}[\log\{(\Delta\rho/\rho_l)+0.043\}+1.35]^{-13.52dp/T}$$
$$q = 14.4\ d_p/T+1.84(\Delta\rho/\rho_l)^{0.116}$$

2.4 Various Factors Influencing p [12]

The curve of increase of dissolution velocity *(-dW/Vdt)* accompanied by an increase in agitator speed *(N)* has two distinct bending points, N_f and N_a as shown in Fig.2.3. N_a is a speed at which air is sucked into the liquid.

In Fig.2.2(a) (KD/D_f) *vs.* $(D^2n\rho/\mu)$ are used instead of *(-dW/Vdt)* vs. *N* for generalization, but the slope of the curves is equal in both diagrams.

Let p_1 denote the slope in the range of agitator speed less than N_f denote that between N_f and N_a, and p_3 that in the range of speed larger than N_a. Usually they are in the order, $p_1 > p_2 > p_3$, and these values vary with $(\rho - \rho_l)$ and d_p. The author correlated p with vaiours factors; density difference, particle diameter and shape factor in the case of slight amount of solid dispersed (2-5g of solid particles in 800 cc liquid).

$$p = f\{(\rho_s-\rho_l)/\rho_l\ ,\ (d_p/D)\ ,\ \phi_s\} \qquad \text{.....(2.15)}$$

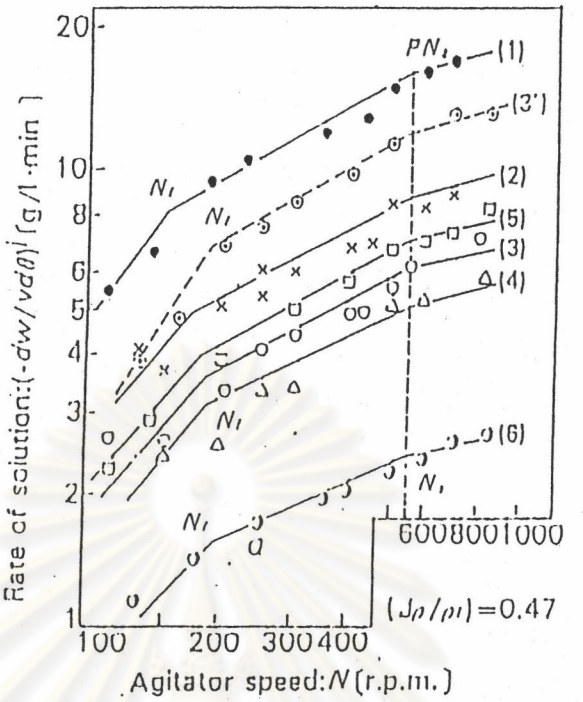

Fig.2.3(a) : Rate of solution vs. agitator speed (H_3BO_3-water system) solid dissolved : (1)-(6) 2.00 g, (3) 4.00 g; sphere : (1) 60-100#, (2) 45-60#, (3), (3') 28-45# (dp = 0.519 mm), (4) 16-28# (dp = 0.737 mm); rhombic crystal : (5) 28-46 # (d = 0.557 mm), (6) 16-28# (dp = 0.858 mm), temp. : 25 °C constant.[21]

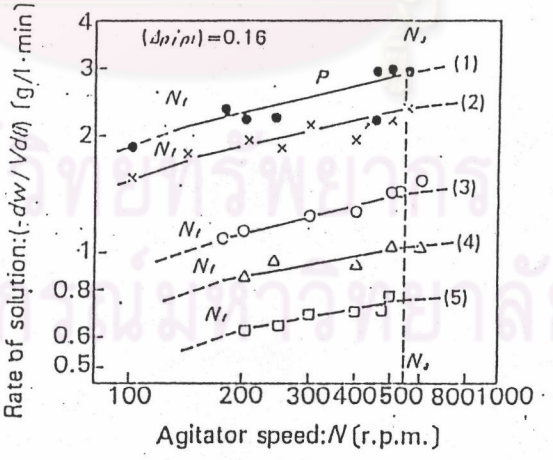

Fig.2.3(b): Correlation of ($-dw/Vd\theta$) vs. N for the crotonic acid-water system.solid used : 0.500 g; size:(1) 28-45#, (2), (3) 16-28#,(4), (5) 10-16#; shape : cubical monoclinic (3), (5), flat monoclinic (1), (2), (4); temp. : 25 °C [21]

A large number of reports have been presented on the rate of mass transfer from suspended solid particles in agitated liquids. This is illustrated in Table 2.1.

As can be seen from Table 2.1 there is a wide divergence of the results and correlations. This is because different approaches have been used to predict mass transfer from suspended solids, dimensional analysis, the slip velocity theory proposed by Harriott [9], the non-steady state model according to Higbie'penetration theory [7] and the Kolmogoroff's theory of local isotropic turbulence [5].

Table 2.1: Dimensionless-Type Correlation Form Various Refferent(12)

Systems	Types Impellers	Baffled	Form	Schmidt number	Renolds number	Correlation	Ref.
Water-benzoic acid	Marine Propeller	No	Tablet	486-2.56x10^6	2.94x10^3-5.3x10^6	$Sh_T=3.5x10^{-4}Re_T^{0.50}Sc^{0.50}$	1
Water-barium chlorine	Turbine Incurved				<6.7x10^4	$Sh_T=2.7x10^{-5}Re_T^{1.40}Sc^{0.50}$	
Water-naphtalene	with 45°				>6.7x10^4	$Sh_T=0.16Re_T^{0.62}Sc^{0.50}$	
Water-benzoic acid Methylate-benzoic acid Benzene-benzoic acid Water-Sodium chloride Water-barium chloride	Turbine incurved with 45° Marine Propeller Turbine with 4-blade	No	Sphere		2.5x10^3-5.0x10^6	$Sh_T=A(Re_p)^p(Sc)^{0.5}(d_p/T)^g$ $0.2<p<0.67$ $-0.8<g<-0.32$	2
Water-benzoic acid Water-boric acid Sucrose Sol:benzoic acid Sucrose Sol:boric.acid	Standard Turbine	Yes	Granular	735-55000	10^4-10^6	$Sh_T=0.052Re_a^{0.833}Sc^{0.50}$	4
Water-benzoic acid	Turbine with 6-blade	Yes	Tablet		24,000-120,000	$Sh_T=3.30Re_a^{0.55}Sc^{0.30}$	5
	Turbine incurved with 45°				40,000-120,000	$Sh_T=0.66Re_a^{0.667}Sc^{0.30}$	
	Marine Propeller				40,000-180,000		
Water-0-aitrophenol	Agitator with 2-blade	No	Shere	1240	43,000-125,000	$Sh_T=0.943Re_a^{0.80}Sc^{0.33}$	6
Water-benzoic acid	Turbine with 4-blade	Yes	Ball	-	>50,000	$Sh_T=8.48Re_a^{0.397}Sc^{0.333}$ $Sh_T=0.0267(2+1.1Re_p^{0.5}Sc^{0.33})N^{0.63}$	10
Water-benzoic acid	Standard Turbine	Yes	Sphere	307-1990	1x10^4-3x10^4	$Sh_p=0.0446Re_p^{0.283}Ga^{0.173}$ $T^{-0.011}(T/d_p)^{0.019}Sc^{0.461}$	14