

CHAPTER 2

LITERATURE REVIEW

2.1 Fick's First Law of Diffusion

BIRD, STEWART and LIGHTFOOT⁽⁶⁾ propose the definition of an unidirectional diffusion in binary constant isothermal system of species A,B

$$N_A = -CD_{AB} \frac{dx_A}{dz} + X_A (N_A + N_B) \quad \text{_____ (1)}$$

The diffusion flux N_A , relative to stationary coordinates, is the resultant of two vectors $X_A (N_A + N_B)$ is the molar flux of A resulting from the bulk motion of the fluid.

The vector $-CD_{AB} \frac{dx_A}{dz}$ is the molar flux of A resulting from the diffusion super imposed on the bulk flow.

The equation (1) is the general definition of diffusivity which the substance A is slightly soluble, so $X_A (N_A + N_B)$ term is neglected.

$$N_A = -CD_{AB} \frac{dx_A}{dz} \quad \text{_____ (2)}$$

which is Fick's first law.

2.2 General Theories of Mass Transfer

The various mass transfer mechanisms which have been postulated to fit experimental data are based on Fick's laws for diffusion processes. Through Fick's first law, which is applicable for steady stated conditions, the following relationship is obtainable :

$$N = k(C_S - C) \quad \text{_____} (3)$$

The assumption implicit in the use of the difference $(C_S - C)$ as a driving force is that a saturation concentration always exists at the phase interface. Although this assumption is common in mass transfer works it is not always valid. It is possible, where mass transfer rates are high, for the interface solute concentration to fall any short of saturation. When this occurs, the driving force is not so great as the indicated difference $(C_S - C)$

2.2.1 The Laminar Film Theory of LEWIS and WHITMAN (7)

The rate constant k in Equation (1) can be interpreted as the ratio of molecular diffusivity to a stagnant film thickness :

$$k = \frac{D}{\delta} \quad \text{_____} (4)$$

This is the basic concept of the film theory proposed by LEWIS and WHITMAN (7) by this concept mass transfer, into or out of a moving fluid phase, occurs by molecular diffusion through a thin film of stagnant fluid at the phase boundary. Mass transfer through the stagnant film is presumed to be slower by orders of magnitude than in the bulk phase and controls the over all single phase rate. As indicated in Equation (2) the rate of mass transfer is directly

proportional to molecular diffusivity and diffusion is assumed to occur only in the direction perpendicular to the interface.

2.2.2 The Penetration Theory of HIGBIE⁽⁸⁾

The penetration or surface renewal theory was introduced by HIGBIE⁽⁸⁾. For discontinuous contact between phase it is assumed that :-

- fresh fluid is brought to the phase boundary for each new contact.
- the fluid, during the period of contact, remains motionless and mass transfer occurs by molecular diffusion in a direction perpendicular to the interface.
- contacting occurs with a regular frequency, that is, the length of time that each new element of fluid remains in contact with the phase boundary is constant

The mass transfer coefficient expressed in relation

$$k = 2 \sqrt{\frac{D_y}{t}} \quad \text{_____} \quad (5)$$

This theory is developed and improved by numerous authors such as DANCKWERT⁽⁹⁾ and HARRIOTT⁽¹⁰⁾

2.3 Correlation of Mass Transfer Coefficient in solid-Liquid Agitation

The rate of mass transfer from 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 particle.

2.3.1 HIXSON and BAUM's correlation

HIXSON and BAUM⁽¹⁾ studied the rate of mass transfer from solid particle 0.25 cm in diameter in liquids agitated by a four-pitched blade paddle and by a marine propeller in unbaffled vessels of various diameters and obtained a dimensionless equation

$$\frac{kD}{D_f} = \frac{D}{x} = C \left(\frac{D^2 n \rho_1}{\mu} \right)^p \left(\frac{\mu}{\rho_1 D_f} \right)^q \quad \text{_____ (6)}$$

or

$$Sh = c Re^p Sc^q \quad \text{_____ (7)}$$

The experimental data is represented by the following equations : Four-pitched - blade paddle

$$Re < 6.7 \times 10^4 ; Sh_a = 2.7 \times 10^{-5} Re_a^{1.4} Sc^{0.5}$$

$$Re \geq 6.7 \times 10^4 ; Sh_a = 0.16 Re_a^{0.62} Sc^{0.5}$$

Propeller

$$3,300 < Re < 330,000 ; Sh_a = 0.0043 Re_a^{1.0} Sc^{0.5}$$

2.3.2 HUMPHREY and VAN NESS's correlation

HUMPHREY and VAN NESS⁽¹¹⁾ measured the rate of solution of $Na_2S_2O_3 \cdot 5H_2O$ crystals suspended in 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 $\frac{d}{D} = 1/3$. The correlation

of the mass transfer coefficients is the same as equation (6) and the numerical values of c, p and q are as follows;

				<u>Re range of application</u>
For propeller	c = 0.47	p = 0.58	q = 0.5	63,000 ~ 330,000
For turbine	c = 0.022	p = 0.87	q = 0.5	31,000 ~ 89,000

2.3.3 BARKER and TREYBAL's correlation

BARKER and TREYBAL⁽³⁾ studied the rate of solution of solid particles suspended in water and 45% sucrose solution in 2 ~ 12 in baffled vessels agitated by a 6-flat-blade turbine. The dissolution rate coefficients of boric acid, rock salt and benzoic acid in several sizes were correlated by the following equation,

$$\ln(10 k) = 1 + 0.85 v^{0.02875} \ln(Re/10^4) \quad \text{_____ (8)}$$

The effect of Schmidt number and particle size was not significant.

By taking 0.833 as an average value for $0.85 v^{0.02875}$, the following dimensionless equation is obtained

$$\frac{kD}{D_f} = 0.02 Re^{0.833} Sc^{0.5} \quad \text{_____ (9)}$$

A large number of reports^(1-3,12-15) have been presented on the rate of mass transfer from suspended solid particles in agitated liquids. This is illustrated in Table 1.

TABLE I

System	Types Impellers	u-unbaffled b-baffled	Form	Sc	Re	Relation proposed	Ref.
Water-benzoic acid	Marine Propeller	u	Tablet	486-2	$2.94 \times 10^3 - 5.3 \times 10^6$	$Sh_T = 3.5 \times 10^{-4} Re_T Sc^{0.50}$	1
Water-barium chloride	Turbine incurved with 45°					$Sh_T = 2.7 \times 10^{-5} Re_T^{1.40} Sc^{0.50}$	
Water-naphtalene						$Sh_T = 0.16 Re_T^{0.62} Sc^{0.50}$	
Water-benzoic acid	Turbine incurved with 45°	u	Sphere	-	$2.5 \times 10^3 - 5.0 \times 10^6$	$Sh_T = A (Re_p^P) (Sc)^{0.5} \left(\frac{d_p}{T}\right)^g$	2
Methylate-benzoic acid	Marine Propeller					$0.20 < p < 0.67$	
Benzene-benzoic acid	Turbine with 4-blade					$-0.80 < g < -0.32$	
Water-benzoic acid	Standard Turbine	- b	Granular	735-55000	$10^4 - 10^6$	$Sh_T = 0.052 Re_a^{0.833} Sc^{0.50}$	3
Water-boric acid							
Sucrose Sol:benzoic acid							
Water-benzoic acid	Turbine with 6-blade	b	Tablet	-	$24,000 - 110,000$	$Sh_T = 3.30 Re_a^{0.55} Sc^{0.30}$	12
	Turbine incurved with 45°					$Sh_T = 0.66 Re_a^{0.667} Sc^{0.30}$	
	Marine Propeller					$40,000 - 180,000$	
Water-o-nitrophenol	Agitator with 2-blade	u	Sphere	1240	$43,000 - 125,000$	$Sh_T = 0.943 Re_a^{0.80} Sc^{0.33}$	13
Water-benzoic acid	Turbine with 4-blade	b	Ball	-	$> 50,000$	$Sh_a = 8.48 Re_a^{0.397} Sc^{0.333}$ $Sh_p = 0.0267 (2 + 1.1 Re_p^{0.5} Sc^{0.33}) N^{0.63}$	14
Water-benzoic acid	Standard Turbine	b	Sphere	307-1990	$1 \times 10^4 - 3 \times 10^4$	$Sh_p = 0.0446 Re_p^{0.283} Ga^{0.173}$ $T^{-0.011} \left(\frac{T}{d_p}\right)^{0.019} Sc^{0.461}$	15

2.4 Definition of Mass Transfer Coefficient

In the case of low flux transfer, the transfer coefficient is defined by the relation

$$dm = kdA \Delta C \quad \text{_____} (10)$$

dm : quantity of dissolved mass per unit time (Kg/s)

dA : exchange area(m²)

ΔC : concentration difference (Kg/m³)

$$\Delta C = C_S - C \quad \text{_____} (11)$$

C_S is the saturated concentration

k is the mass transfer coefficient

For isothermal, the concentration C_S is constant. On the other hand the liquid concentration C per time is proportional to the mass of solid dissolved

$$m = V \frac{dC}{dt} \quad \text{_____} (12)$$

Substituting for dm in equation (10)

$$kA(C_S - C) = V \frac{dC}{dt} \quad \text{_____} (13)$$

The term $\frac{kA}{V}$ is constant, integrating equation (13) : gives

$$\ln \frac{C_S - C}{C_S - C_0} = -\frac{kAt}{V} \quad \text{_____} (14)$$



or

$$k = \frac{1}{A} \frac{V}{t} (C - C_o) \frac{1}{\Delta C_{ML}} \quad \text{_____ (15)}$$

$$\text{where } \Delta C_{ML} = \frac{(C_S - C_o) - (C_S - C)}{\ln \frac{C_S - C_o}{C_S - C}} = \frac{C_S - C}{\ln \frac{C_S - C_o}{C_S - C}}$$

In this expression, $\frac{V}{t} (C - C_o)$ is mass transfer Equation (15) becomes :

$$k = \frac{m}{A \Delta C_{ML}} \quad \text{_____ (16)}$$

2.5 Flow Pattern

Agitators are used to produce flow and subsequently, turbulence in a liquid mass. Each type of agitator cause high velocity liquid to flow through a vessel in a specific path, refer to as a flow pattern. For example flat and curved blade turbines produce radial flow pattern, marine type propeller and pitch blade turbine produce axial flow pattern, Table 2. is a summary of the types of agitators that are used in this work.

If either the marine propeller or any of the impeller agitators are used in an unbaffled vessel containing low viscosity liquid, vortexing develops. The liquid swirls in the direction of the agitator rotating, causing a drop in liquid level around the agitator shaft. Vortexing increases with impeller speed until eventually the vortex passes through the agitator. Gas bubbles

will be sucked into the bulk fluid. The mixing efficiency of vortexing systems is usually lower than for geometrically similar nonvortexing systems. This can be avoided by putting baffles into the vessel. Baffles is fixed perpendicular to the vessel wall.

The basic principles which related fluid velocities and equipment geometry are applicable also to rotating impellers in agitated vessels.

Radial Flow

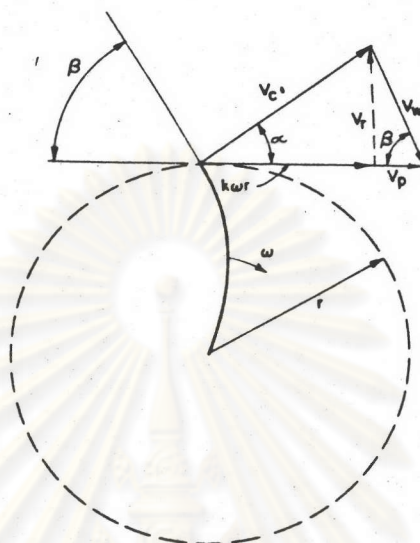
In Fig.(1) are shown the velocity vectors at the periphery of a curved-blade turbine impeller. The following equations can be written from inspection of this diagram.

$$\begin{aligned}
 V_{\omega}^2 &= V_c^2 + V_p^2 - 2V_p V_c \cos \gamma \\
 V_{\omega}^2 &= V_r^2 + (\omega r - k\omega r)^2 \\
 V_r &= V_{\omega} \sin \beta \\
 V_c \cos \gamma &= k\omega r \\
 V_r &= \sin \gamma \left[(k\omega r)^2 \tan^2 \gamma + (r - k\omega r)^2 \right] \\
 V_p &= \omega r
 \end{aligned}$$

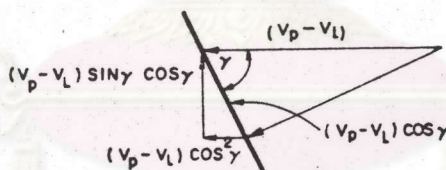
Axial Flow

In Fig. (1) are shown the velocity vectors at the periphery of a pitched blade turbine. In this figure, V_p is the peripheral blade velocity, ωr , and γ is the angle of pitch of the blade face. The absolute velocity of the liquid is V_L . The difference $(V_p - V_L)$ is the velocity of the liquid relative to the blade. Velocity components of the fluid approaching the blade which are in an axial

Figure.1 Discharge velocity



for a curved-blade turbine



for a pitched-blade turbine

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or radial direction are neglected or assumed to be zero. The fluid is assumed to leave the blade in a direction parallel to the face of the blade. The magnitude of this velocity in a plane which is perpendicular to the plane of the blade and parallel to the axis of rotation of the blade is equal to $(V_p - V_L) \cos \gamma$. The vertical component of this velocity relative to the blade is $(V_p - V_L) \sin \gamma \cos \gamma$ and the tangential component is $(V_p - V_L) \cos^2 \gamma$. The velocity of the latter relative to the liquid approaching the blade is $V_p - (V_p - V_L) \cos^2 \gamma - V_L$ which is equal to $(V_p - V_L) \sin^2 \gamma$. The radial velocity of fluid leaving the inclined blade was assumed to be equal to the tangential velocity of fluid leaving the blade minus the tangential velocity of fluid entering. This radial velocity is $(V_p - V_L) \sin^2 \gamma$.

A flow equation for a marine propeller is derived in a similar way. In this case, the angle, γ , is a function of the radial distance from the axis of rotation.

$$\tan \gamma = P/2 \pi r$$

where P is the propeller pitch. Pitch is related to $\sin \gamma$ and $\cos \gamma$ as follows :

$$\sin \gamma = P / (P^2 + 4\pi^2 r^2)^{1/2}$$

$$\cos \gamma = 2\pi r / (P^2 + 4\pi^2 r^2)^{1/2}$$

2.6 Suspension of Solid Particles

The state of suspension of solid particles in liquid refers to the instant at which all solids are in circulation and none is resting on the vessel bottom. Suspension of solids in a liquid medium will be obtained when the rising velocity of the liquid phase equal or exceeds the settling velocity of the particles. Fluid velocity and direction are function of impeller selection and of vessel contour. Particle settling velocity is a function of gravitation force, fluid drag and several hindering factors such as density difference, size and shape of the solid particles.

Zwietering⁽¹⁶⁾ endeavored to derieve relations of general validity for the optimum arrangement of a mixer for suspending solid particles in a liquid. The equation was modified by mean of dimensional analysis.

$$N_c = \phi \frac{(T)}{D}^{1.4} \frac{g^{0.45} (\rho_p - \rho)^{0.45} 0.1 d_p^{0.2} (100 R)^{0.13}}{D^{0.85} \rho^{0.55}}$$

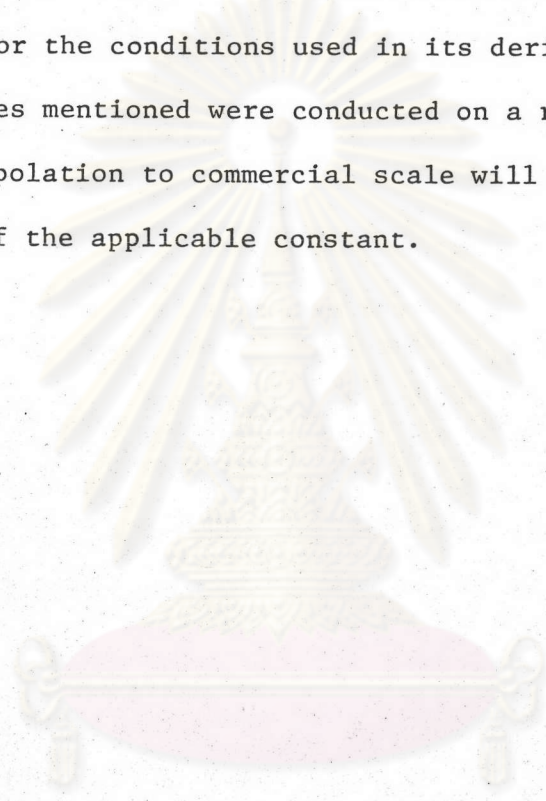
Oyama and Endoh⁽¹⁷⁾ developed an impeller power per mass of liquid relation for their critical impeller speed at which "complete" suspension was attained :

$$\left(\frac{P_c g_c}{m_s} \right)^{2/3} = g d_p^{1.3} \frac{(\rho_p - \rho_1)}{16 \rho_1}$$

Nienow⁽³⁰⁾ propose the relation :

$$N_S = SV^{0.1} d^{0.2} \frac{(g\Delta\rho)^{0.45}}{\rho} \frac{(X)^{0.13}}{L^{0.85}}$$

The above investigations extended from laminar to turbulent conditions. In each study, it was noted that additional speed above the critical was required for complete distribution of solids phase throughout the entire fluid mass. Each of the correlating relationship is valid for the conditions used in its derivation. However, all of the studies mentioned were conducted on a relatively small scale, and extrapolation to commercial scale will necessitate a re-examination of the applicable constant.



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