CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 Theory and Physical Principle for Gas Absorption in Packed Absorber.

2.1.1   Absorption

Absorption, or gas absorption, is a mass transfer unit operation used in chemical industry to separate gases by scrubbing a gas mixture with a suitable liquid (called absorbent) or to produce chemical product by feed inlet gas to react with raw liquid material. One or more of the component of the gas mixture dissolve, react or is absorbed in the liquid. The result of absorption is in forms a physical solution with the liquid or the new substance when chemical reaction is occurred in absorption process.

The object of gas absorption may be gas purification (such as removal of air pollutants from process vented gases or contaminants from gases in production process), product recovery, or production of solutions of gases for various purposes. One examples for application of absorption processes is absorption of hydrochloric vapor by water in air pollution control application.

Gas absorption is usually operated in vertical column as shown in Figure 2.1. Liquid (solvent) is fed at the top of the absorber and the gas mixture flowed into the bottom. The result of countercurrent flow of gas and liquid in absorber was in form solution or mixture of absorbed gas in liquid and left the absorber at the bottom. The absorber which in study was packed column. The packed column was normally cylinder shell which filled inside by packed elements(called packing), packing functional was increase of contacting surface for gas and liquid when its flowed through packed bed. The good packing must had a large internal surface at low pressure drop and corrosion resistance. For normal operation packing is randomly filled in packed column.

The advantages of packed columns were included simple to construction and, the tower diameter is not too large if compared with other absorber at the same capacity and low construction cost. These columns are preferred for corrosive gases because packing could be made from ceramic or plastic materials.
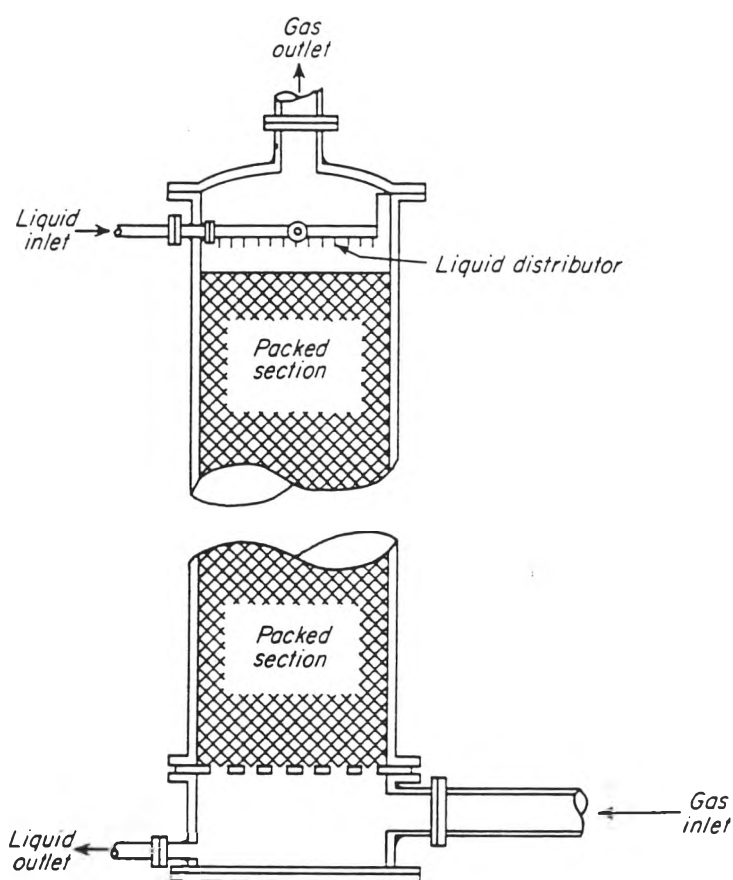
Figure 2.1 Basic diagram of packed absorber.

The fundamental principles required for study the process of gas absorption in packed absorber were the solubility of the absorbed gas in liquid which is considered with molecular diffusion in both gas and liquid phase to calculate the rate of mass transfer, information for design packed absorber (column sizing) which are included the fundamental

design concepts based on mass and heat balance, physical properties of both gas and liquid and properties of packings.

2.1.2　Gas Solubility

At equilibrium condition, a component of a gas in contact with a liquid, gas phase is equal liquid phase fugacity. For ideal solutions Raoult's law can used as relation

$$y_A = \frac{p_s}{P} x_A \qquad (2\text{-}1)$$

where y_A is the mole fraction of A in the gas phase, P is the total pressure, p_s is the vapor pressure of pure A, and x_A is the mole fraction of A in the liquid. For gas and liquid which condition nearly ideal solution molecules, Henry's law is applied in relation as:

$$y_A = \frac{H}{P} x_A \qquad (2\text{-}2)$$

where H is Henry's constant, H is dependent on temperature. A more general way to express solubilities of the vapor-liquid equilibrium by mean of constant m defined by

$$y = mx_A \qquad (2\text{-}3)$$

The value of m, also known as equilibrium K value. When equation (2-1) or (2-2) is applicable at constant pressure and temperature (equivalent to constant m in equation (2-3) a plot of y vs x for a given solute is linear from the origin. Generally, for nonideal solutions or for nonisothermal conditions, y is not linear function of x and must be determined from experimental data. The y-x plot, when used to absorber design, is called the equilibrium line.

2.1.3   Mass Transfer Concepts

Mass Transfer Coefficients and Driving Forces. In packed absorber size determination, the equilibrium solubility of the solute in the solvent is considered and then transfer rate at the equilibrium between gas and liquid are considered; i.e., the rate of the solute transfer from the gas to the liquid phase, rate of solvent transfer to gas phase and heat transfer between both phases. At first, mass transfer rate from gas phase to liquid phase must have known before determine other transfer. In mass transfer study, theoretical model of gas-liquid interface is considered. Mass transfer from bulk flow of gas to bulk flow of liquid is occurred at interface area of gas and liquid, at the interface the fluid motions were slowly and molecular could diffuse through interface as a mechanism of mass transfer. At the interface assume that the transfer occurred immediately and transfer until equilibrium was exist at interface between two phases, mass transfer resistance at ideal interface is zero.
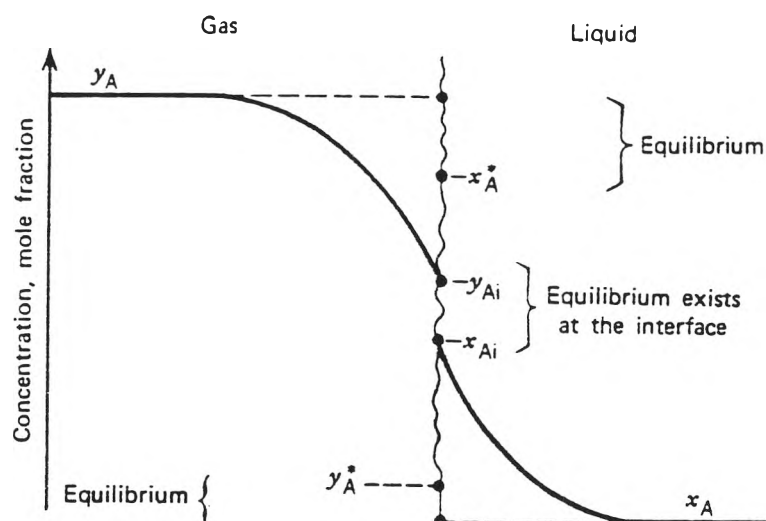

Figure. 2.2 The two-film concept: y_A and x_A are the concentrations in the bulk of the phases; y_{Ai} and x_{Ai} are the actual interfacial concentrations at equilibrium; y^*_A and x^*_A are the hypothetical equilibrium concentrations which would be in equilibrium with the bulk concentration of the other phase.*

* From Kirk-Othmer, "Encyclopedia of chemical technology.", fourth edition, vol 1., John wiley & son, New York, 1991, page 43

The concentration gradient is represented driving force of mass transfer as shown in Figure 2.2. Mass transfer process was continuously until concentration between two phase reached equilibrium condition. From mass transfer at interface studied, the rate of mass transfer are proportional to the displacement from equilibrium and the rate equation for the gas and liquid films are

$$N_A = k_G(P_A - P_{Ai}) = k_G P(y_A - y_{Ai}) \qquad (2\text{-}4)$$

$$N_A = k_L(c_{Ai} - c_A) = k_L \rho(x_{Ai} - x_A) \qquad (2\text{-}5)$$

where $y_A - y_{Ai}$ and $x_{Ai} - x_A$ are concentration driving forces, k_G is the gas-phase mass transfer coefficient, and k_L is the liquid-phase mass transfer coefficient.

Mass transfer rates may also be expressed in terms of an overall gas-phase driving force by defining a hypothetical equilibrium mole fraction y_A^* as the concentration which would be in equilibrium with the bulk liquid concentration $(y_A^* = mx_A)$:

$$N_A = K_{OG}P(y_A - y_A^*) \qquad (2\text{-}6)$$

The relationship of the overall gas-phase mass transfer coefficient K_{OG} to the individual film coefficients may be found from equations (2-4) and (2-5), assuming a straight equilibrium line:

$$N_A = k_G P(y_A - y_{Ai}) = k_L \rho(1/m)\,(y_{Ai} - y_A^*)$$

and by comparison with equation (2-6)

$$\frac{1}{K_{OG}} = \frac{1}{k_G} + \frac{mP}{k_L \rho} \qquad (2\text{-}7)$$

Expressions similar to equations (2-6) and (2-7) may be derived in terms of an overall liquid-phase driving force. Equation (2-7) represented an addition of the resistance to mass transfer in the gas and liquid films.

2.1.4 Nonisothermal Gas Absorption in Packed Absorber.

Solution to the design problem of nonisothermal packed gas absorber, based on graphical and computational techniques which were developed by Isami Yoshifuki(4). From his research, packed absorber model which consist physical property data, the mass transfer resistance in gas phase and/or liquid phase, the heat effects e.g., heat of solution, latent heat of vaporization and sensible heat transfer in both phases are established.

In the flowgraph/model construction the following consumption are made
1) Adiabatic gas absorption in a packed tower with considered heat effect in absorption is established.
2) Liquid-phase resistance to heat and mass transfer are ignored and the effect of solvent evaporation is considered.
3) Heat of solution, latent heat of vaporization and molar specific heat were constant.

The problem is called for the determination of tower height from the data of tower bottom tower top physical properties and volumetric heat and mass transfer coefficients.

An algorithm for the problem of the packed tower process has previously studied by other researcher. Yoshifuki presented a calculation procedure of sequential cell flowgraph construction. In paper, the procedure consisted of tabulation of the fundamental equations, transformation of equation to flowgraph unit, and formation of the n-th cell flowgraph, and construction of a sequential cell flowgraph.

As the first step, packed absorber model is separated to n-th cell along height of packed column as shown in Figure 2.3. The n-th cell model of the packed tower and the related fundamental equations are shown in Figure 2.4 and Table 2.1, respectively.
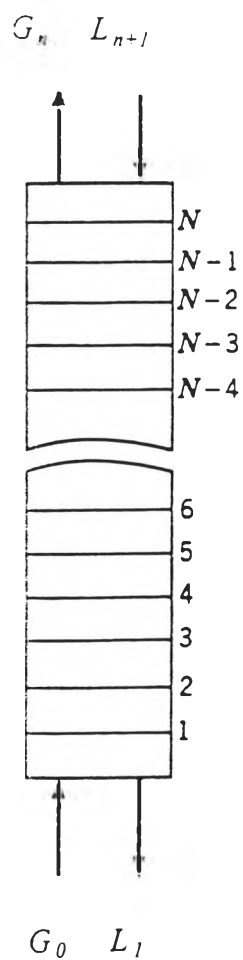
$$G_n \qquad L_{n+1}$$

N

$N-1$

$N-2$

$N-3$

$N-4$

6

5

4

3

2

1

$$G_0 \qquad L_1$$

Figure 2.3 Packed absorber is separated to n-th cell model.

y_n, G_n, t_{Gn}, w_n $x_{n+1}, L_{n+1}, t_{Ln+1}$

y_n N_{An} y_{An} N_{An} x_n

y_n q_{An}

y_n N_{An} t_{Ln} q_{Ln} t_{Ln}

y_n q_{An} w_{an} N_{Wn}

y_n q_{Wn}

Δz

$y_{n-1}, G_{n-1}, t_{Gn-1}, w_{n-1}$ x_n, L_n, t_{Ln}
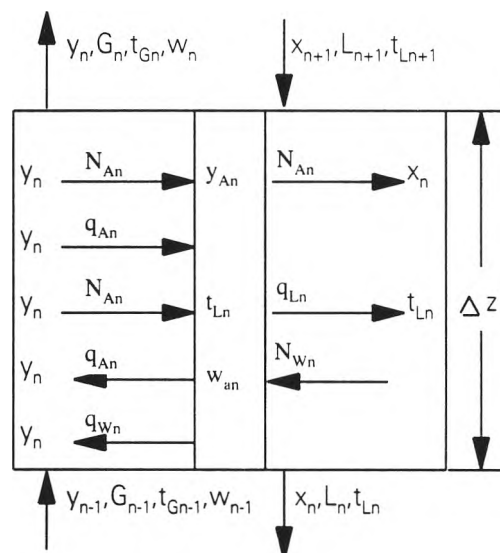
Figure 2.4 n-th cell model (From Isami Yoshifuki, "Journal of chemical

Engineering of   Japan.", Vol1, No.5, 1988, page 539)

Table 2.1 Fundamental equation for n-th cell model

Fundamental equations		
equation number		
1. Mass balance gas phase, n-th cell	$G_{n-1} + N_{Wn} = G_n + N_{An}$	(2-8)
2. Solute mass balance in gas phase, n-th cell	$y_{n-1}G_{n-1} = y_nG_n + N_{An}$	(2-9)
3. Solvent mass balance in gas phase, n-th cell	$w_{n-1}G_{n-1} + N_{Wn} = w_nG_n$	(2-10)
4. Mass balance liquid phase, n-th cell	$L_{n+1} + N_{An} = L_n + N_{wn}$	(2-11)
5. Solute mass balance in liquid phase, n-th cell	$x_{n+1}L_{n+1} + N_{An} = x_nL_n$	(2-12)
6. Enthalpy balance gas phase, n-th cell	$C_{PG}t_{Gn-1}G_{n-1} = C_{PG}t_{Gn}G_n + q_{Gn}$	(2-13)
7. Enthalpy balance liquid phase, n-th cell	$C_{PL}t_{Ln+1}L_{n+1} + q_{Ln} = C_{PL}t_{Ln}L_n$	(2-14)
8. Overall heat balance, n-th cell	$q_{Ln} = q_{An} + q_{Gn} - q_{Wn}$	(2-15)
9. Solute mass transfer rate (gas to liquid), n-th cell	$N_{an} = k_ya(y_n - y_{Sn}) * \Delta Z$	(2-16)
10. Solvent mass transfer rate (liquid to gas), n-th cell	$N_{Wn} = k_wa(w_{Sn} - w_n) * \Delta Z$	(2-17)
11. Heat of dilution, n-th cell	$q_{An} = \lambda_A N_{An}$	(2-18)
12. Heat of evaporation, n-th cell	$q_{Wn} = \lambda_w N_{Wn}$	(2-19)
13. Heat transfer from gas to liquid, n-th cell	$q_{Gn} = h_Ga(t_{Gn} - t_{Ln})\Delta Z$	(2-20)
14. Vapor-liquid equilibrium relation	$y_{Sn} = K_nx_n$	(2-21)
15. Equilibrium constant	$K_n = f(t_{Ln})$	(2-22)
16. Vapor pressure of liquid in gas	$w_{Sn} = p_{Wn} / P$	(2-23)
17. Vapor pressure of quid phase	$p_{Wn} = f(t_{Ln})$	(2-24)
18. Height of packed column	$Z = N * \Delta Z$	(2-25)

The number of equation is $17N+1$, and the number of variables is $17N$ (L, G_n, x_w, $y_W, w_n, q_{Ln}, q_{An}, q_{wn}, q_{Gn}, N_{An}, N_{wn}, y_{sn}, w_{sn}, t_{Ln}, t_{Gn}, P_{wn}, K_n$) and 9 are L_{n+1}, x_{n+1}, t_{Ln+1}, G_0, y_0, w_0, t_{G0}, Z, N). Known variables are specific heat, volumetric mass and heat transfer coefficients and so forth are not counted. And the number of degrees of freedom is $(17N + 9) - (17N+1) = 8$, which is specified to $G_B(= G_0)$, $L_T(= L_{n+1}), y_B(= y_0), w_B(= w_0)$, $t_{Gn}(=t_{G0})$, $y_T(=y_n), x_1(=x_{n+1})$ and $t_{LT}(=t_{Ln+1})$

As the second step, each of the fundamental equations is transformed to overall mass balance equation to find inlet variables for n-th cell calculation. From the fundamental equations, the following equations are derived, from equation (2-8), (2-9)

$$G_{n-1} + N_{Wn} = G_n + N_{An}$$
$$y_{n-1}G_{n-1} = y_nG_n + N_{An}$$

From equation (2-8) $\quad N_{An} = G_{n-1} - G_n + N_{Wn}$

$$\therefore \Sigma N_{An} = (G_B - G_1 + N_{W1}) + (G_1 - G_2 + N_{W2}) + ... + (G_{n-1} - G_T + N_{WT})$$

$$= G_B - G_T + \Sigma N_{Wn} \tag{2-26}$$

From equation (2-9) $\quad N_{An} = y_{n-1}G_{n-1} - y_nG_n$

$$\therefore \Sigma N_{An} = (y_BG_B - y_1G_1) + (y_1G_1 - y_2G_2) + ... + (y_{n-1}G_{n-1} - y_TG_T)$$

$$= y_BG_B - y_TG_T \tag{2-27}$$

From equation (2-26) $\quad G_T = G_B + \Sigma N_{Wn} - \Sigma N_{an}$

Substitute G_T into equation (2-27)

$$\Sigma N_{An} = y_BG_B - y_T(G_B + \Sigma N_{Wn} - \Sigma N_{An})$$
$$= y_BG_B - y_TG_B - y_T\Sigma N_{Wn} + y_T\Sigma N_{An}$$
$$\Sigma N_{An} - y_T\Sigma N_{An} = y_BG_B - y_TG_B - y_T\Sigma N_{Wn}$$
$$(1 - y_T)\Sigma N_{An} = G_B(y_B - y_T)G_B - y_T\Sigma N_{Wn}$$

$$\therefore \Sigma N_{An} = \frac{G_B(y_B - y_T)}{(1 - y_T)} - \frac{y_T\Sigma N_{Wn}}{(1 - y_T)} \tag{2-28}$$

$$\Sigma N_{An} = G_B(y_B - y_T) / (1 - y_T) - y_T\Sigma N_{Wn} / (1 - y_T) \tag{2-29}$$

$$L_B = L_T + \Sigma N_{An} - \Sigma N_{Wn} \tag{2-30}$$

$$x_B = ((x_T L_T) + \Sigma N_{An}) / L_B \tag{2-31}$$

$$N = n : \quad y_n < y_T \tag{2-32}$$

Calculation is started at the first cell using the variables G_B, y_B, w_B, t_{GB}. L_B, x_B and appropriate value of t_{LB}, ΣN_{tn} and ΔZ (e.g. 0.01). Cell-by-cell calculation based on the n-th cell flowgraph shown in Figure 2.4 must be continued until the N-determining equation (2-32) is reached, and then the tower height Z is calculated by equation (2-25).
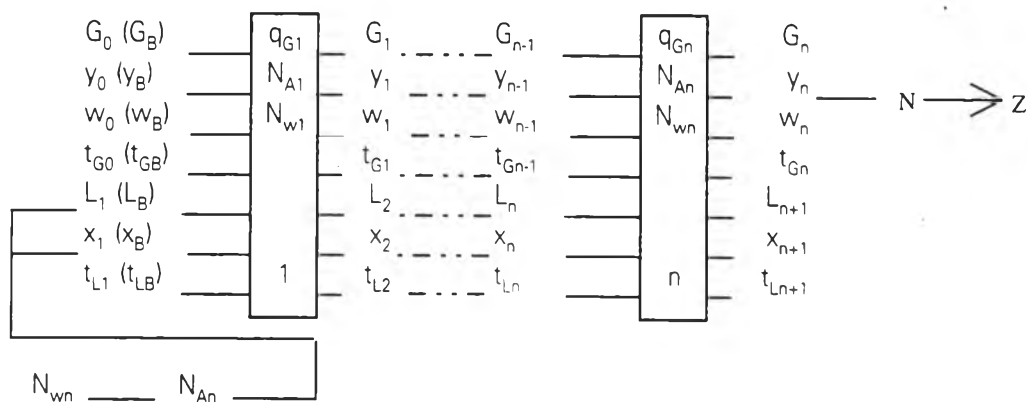
Figure 2.5 Sequential cell flow graph (From Isami Yoshifuki, "Journal of chemical Engineering of Japan.", Vol 21, No.5, 1988, page 540)

2.1.7   Simultaneous Heat and Mass Transfer in Hydrochloric Vapor Absorption

In gas absorption process as hydrochloric vapor absorption process which heat and mass transfer between gas and liquid in packed column are simultaneously occurred. In hydrochloric vapor absorption by water process involved heat transfer from gas phase to liquid phase and from liquid phase to gas phase. The rate of heat transfer from gas phase to liquid phase per unit area is given by equation (2-20).

$$q_{Gn} = h_G a \; (t_{Gn} - t_{Ln}) \Delta Z$$

water is evaporated simultaneously at rate which calculated by equation (2-21)

$$N_w \;\; = \;\; k_w a \; (w_{sn} - w_n) \Delta Z$$

where t_{Gn} and t_{Ln} are temperature of gas and liquid and heat of water evaporation is heat transfer from heat of hydrochloric dilution in water is given by equation (2-18)

$$q_{An} = \lambda_A \, N_{An}$$

Heat for water evaporation is given by equation (2-19)

$$q_{wn} = \lambda_w N_w$$

From enthalpy balance in gas phase and liquid phase in n-th cell of packed column, total heat transfer from gas to liquid is given by equation (2-15)

$$q_{Ln} \;\; = \;\; q_{An} + q_{Gn} - q_{wn}$$

2.1.8 Mass Transfer Coefficient

K. Onda, H. Takeuchi and Y. Okumoto researched mass transfer coefficient between gas and liquid phases in packed column(1), which generated the correlations from result of many experimental calculated data for a variety of packings with gas absorption and desorption using water and organic solvents. The gas phase correlation also includes data on the vaporization of pure liquids. Most of the experimental data divided within ± 20 percent of the value calculated from the correlation, but some data deviate higher than ± 50 percent. For some data which had enough are high deviation maybe due to insufficient data. These correlations include data on the following packings:

Raschig rings :   1/2 to 2 in.

Berl saddles :   1/2 to 1 1/2 in.

Pall rings. :   1 in.

Spheres :   1/2 and 1 in.

Rods :   1/2 and 1 in.

The correlations are in terms of mass-transfer coefficients, which can be used to find to heights of transfer units, or height of packed absorption tower. They also developed a method for determining the actual interfacial area between phases in the wetted packing, that mean mass transfer coefficient can be calculate directly if had enough required variable.

Liquid phase:

$$k_L \left(\rho_L / \mu_L g \right)^{1/3} \quad = \quad 0.0051 \left(G_L / a_v \, \mu_L \right)^{2/3} \left(\mu_L / \rho_L \, D_L \right)^{-1/2} \left(a_V D_p \right)^{0.4} \qquad (2\text{-}33)$$

Gas phase:

$$k_G RT / a_V D_V P \quad = \quad C_I \left(G_v / a_v \, \mu_V \right)^{0.7} \left(\mu_V / p_V D_V \right)^{1/3} \left(a_V D_p \right)^{-2.0} \qquad (2\text{-}34)$$

The expression for a_w, the wetted surface of the packing, is

$$a_w / a_v \quad = \quad 1 - exp \left[-1.45 \left(\sigma_c / \sigma \right)^{0.75} \left(G_L / a_v \mu_L \right)^{0.1} \times G_L^2 a_v / \rho_L^2 g \right)^{-0.05}$$
$$\left(G_L^2 / \rho_L \sigma a_v \right)^{0.2} \right] \qquad (2\text{-}35)$$

C_I = dimensionless constant. C_I = 5.23 for packing size larger than 1/2 in. ; C_I = 2.0 for packing size less than 1/2 in.

2.2 Hydrochloric Vapor Absorption.

2.2.1 Equilibrium Data of Hydrochloric Absorption by Water.

Absorption of hydrochloric vapor by water was studied by many researchers, but the most favorite paper is the research of Oldershaw C.F., Simerson L., Brown T., and Radcliffe F.(2) due to result in the paper usually use as reference data for another researcher. In that paper shown results of adiabatic and isothermal absorption of hydrochloric by water in effect of inert gas as methane and air by various operating condition. The result of adiabatic absorption of hydrochloric at 1 atmosphere in Figure 2.6 could use to equilibrium data for this thesis.
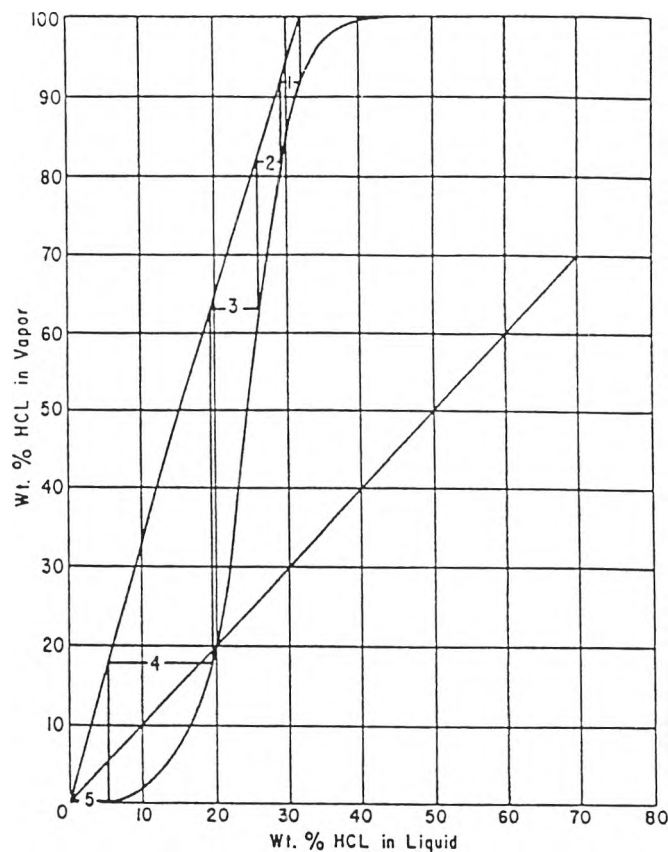

Figure 2.6 x-y diagram for adiabatic absorption of hydrochloric at 1 atmosphere. (From C.F.Oldershaw, L. Simerson, T.Brown and F. Radcliffe, Trans. Sect., "Chem. Eng. Prog." Vol.43, No.7, P.371, 1947.

From relation of equilibrium of hydrochloric vapor and hydrochloric content in liquid at low hydrochloric concentration in liquid (water) as plot in equilibrium curve in Figure 2.6 shown that hydrochloric vapor absolutely dissolved in liquid or mean that hydrochloric concentration of hydrochloric in gas phase which equilibrium with low hydrochloric concentration in packed column equal zero is used in this thesis.

2.2.2 Hydrogen Chloride Absorption in Industry

The absorption of hydrogen chloride in water or in diluted hydrochloric acid is a very important operation in the manufacture of commercial hydrochloric acid. It also important as a pollutant prevention process because hydrogen chloride is toxic gas, vented directly to atmosphere unallowable. In chemical process where hydrochloric vapor is present as a composition in gas streams, it can directly removed by washing with water. The only main factors are the high corrosiveness of the resultant of hydrochloric solution in water and the problem of its disposal.

The heat of solution is considerable, especially in Hydrochloric acid production, and if it is desired to effect very complete removal of hydrogen chloride from a concentrated gas stream or to produce a solution of maximum concentration, heat removal is necessary. This may be accomplished by using cooled absorbers or by recycling the acid through a cooler and back to the absorption unit. But in hydrochloric vapor from storage tank absorption heat effect is lower than production process only packed absorber could use in this case as adiabatic absorber.

Because of the very high solubility of hydrochloric in water and the rapidity with which the reaction with water occurs, the absorption is completely gas-film controlled. With concentrated gas streams, in which the low concentration of inert gas permits rapid diffusion through the gas stream, absorption is extremely rapid and very simple devices such as externally cooled, wetted-wall columns may be used. With less concentrated gases or less flow rate stream, the absorption rate is reduced and plastic-packed towers may be employed.

2.2.3   Hydrochloric Vapor Packed Absorption Towers.

Packed towers had less pressure drop and are more easily designed for resisting acid corrosion because of the wide variety of plastic packing. Main component of packed tower is tower vessel and packing, support part and liquid distributor.

Hydrochloric absorption processes are highly corrosive and towers are constructed of corrosion resistant materials to overcome corrosion problems. The nonmetal towers as fiberglass reinforced plastic is normally used, because of the low cost and vigorous of fiberglass.

Plastic packing is most appropriate packing in hydrochloric vapor absorption due to corrosion resistance property and wide range of size and type of packing. Packing type and size are depend on budget and packing efficiency.

2.3   Radiation Heat Transfer in Hydrochloric Storage System.

Study for radiation heat transfer in hydrochloric acid storage system was necessary for prediction of gas vaporization rate from storage tank because hydrochloric and water are vaporized by heat in hydrochloric solution which transferred from overall environment of tank. Heat transfer from the environment was in form of radiation heat transfer.

2.3.1   Thermal Radiation.

Radiation heat transfer is the physical mechanism of electromagnetic radiation emitted by a body. Radiation rate between two bodies depends on temperature difference between two bodies and its temperature. Electromagnetic radiation is widely range of spectrum, radiation range from infrared to ultraviolet is main energy transfer in common radiation, is referred to thermal radiation.

For thermal radiation in all wavelengths, the energy emitted is proportional to absolute temperature and is described by Stefan-Boltzmann relation(6).

$$E_b = \theta T^4 \qquad\qquad W/m^2 \qquad\qquad (2\text{-}36)$$

where θ is the Stefan-Boltzmann constant and has the value = 5.669×10^{-8} $W/m^2 . K^4$, E_b is the energy radiated per unit time and per unit area by the ideal radiator and T is in degree Kelvin.

2.3.2 Radiation Properties

In radiation heat transfer study, the required physical properties of material was emissivity and absorptivity which was indicator of radiation resistance. When radiation heat is transferred to material surface, the radiation are split in three parts as shown in Figure 2.7.
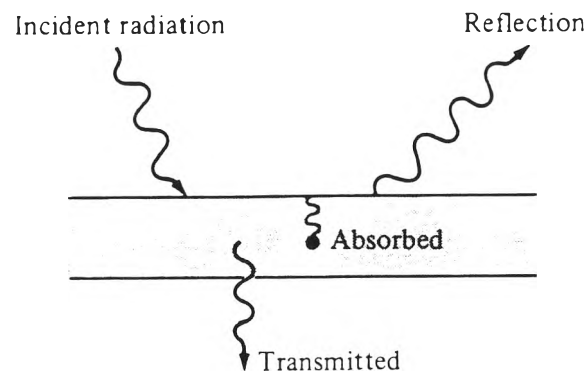

Figure 2.7 Schematic diagram shown effect of incident radiation. (From J.P. Holman, "Heat Transfer", McGraw-Hill book company, Singapore, 1986, page 376.

Absorptivity of material is defined by relation

$$\frac{E}{E_b} = \alpha \qquad (2\text{-}37)$$

The emissive power of a body E was the energy emitted by the body per unit area and per unit time, E_b is the energy emitted per unit time and per unit area from the black body at the same size and at the same temperature. Absorptivity is property of material for over all wavelengths, it represented controlling property in heat exchange by radiation.

2.3.3 Solar Radiation

Solar radiation is a thermal radiation from the sun. Radiation intensity on the surface of the earth is depend on atmospheric condition, time of the year and the angle of the solar rays on the surface of the earth.

When the solar radiation reached objects on the surface of the earth, part of radiation is absorbed by the objects and the other is reflected to the atmosphere. Absorption rate for solar radiation of the objects is depended on absorptivity of surface of objects. The absorptivity for solar radiation is deferent from absorptivity for low temperature radiation (at 25°c) as shown in Table 2.2.

Table 2.2 Comparisons of Absorptivities of Various Surfaces to Solar and Low-Temperature Thermal Radiation

Surface	Absorptivity	
	For solar radiation	For low-temperature radiation ~25°C
Aluminum, highly polished	0.15	0.04
Copper, highly polished	0.18	0.03
Tarnished	0.65	0.75
Cast iron	0.94	0.21
Stainless steel, no. 301, polished	0.37	0.6
White marble	0.46	0.95
Asphalt	0.9	0.9
Brick, red	0.75	0.93
Gravel	0.29	0.85
Flat black lacquer	0.96	0.95
White paints, various types of pigments	0.12-0.16	0.90-0.95

The absorptivity for solar radiation is used in calculation for radiation heat transfer from the solar to the object by given equation.

$$Q_s = \left(\frac{Q}{A}\right)_{sun} \alpha_{sun} A_s \qquad (2\text{-}38)$$

Where A_s = total surface area of object which is exposed to a solar flux (m^2)

2.3.4   Energy Balance of Hydrochloric Acid Storage Tank.

Energy balance for hydrochloric acid storage tank is set at steady state condition, and by assumption that hydrochloric acid storage tank is only exchanged heat with the environment in form of radiation heat transfer. Convective heat transfer from air is neglected. Temperature of liquid and gas in storage tank are constant and temperature of tank surrounding is constant. Schematic involved heat transfer for hydrochloric heat transfer is shown in Figure 2.8.
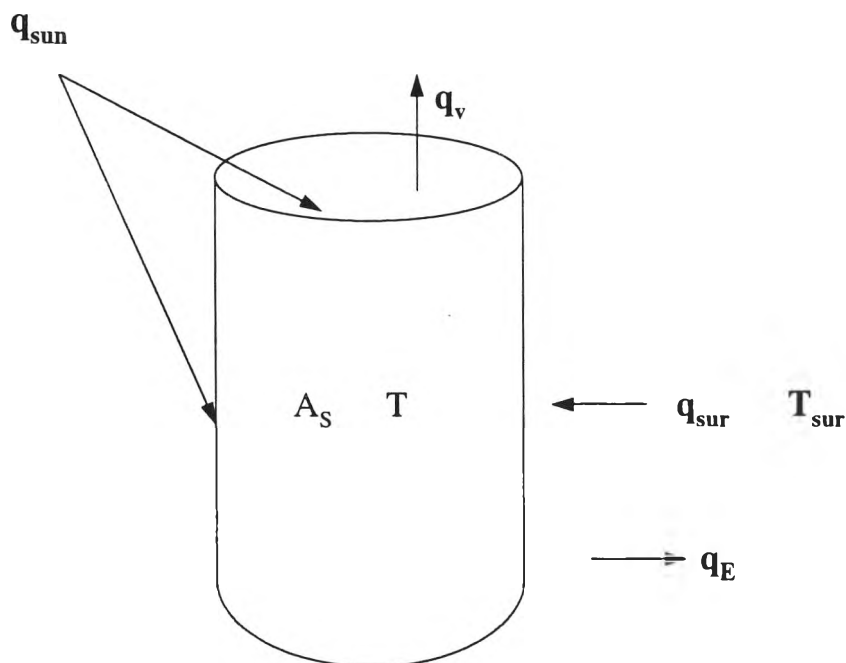

Figure 2.8 Schematic heat transfer for hydrochloric acid storage tank.

Energy balance equation for hydrochloric acid storage tank is

$$Q_{sun} + Q_{sur} = Q_E + Q_v \qquad (2\text{-}39)$$

Q_{sun} = heat transfer from solar radiation (kJ/S)

$$= \left(\frac{Q}{A}\right)_{sun} \alpha_{sun} A_s \times 10^{-3} \qquad (2\text{-}40)$$

Where A_s = total surface area of the storage tank (m^2)

Q_{sur} = Emissive heat transfer from surrounding to storage tank

$$= \theta\, T_{sur}^{4} . A_s . 10^{-3} \qquad \text{(kJ/S)} \qquad (2\text{-}41)$$

Q_E = Emissive heat transfer from storage tank to surrounding

$$= \theta\, T^{4} . A_s . 10^{-3} \qquad \text{(kJ/S)} \qquad (2\text{-}42)$$

Q_V = Heat of hydrochloric and water vaporization

$$= \lambda_y\, y\, G_V + \lambda_W\, w\, G_V \qquad \text{(kJ/S)} \qquad (2\text{-}43)$$