2019-2020 SPRING SEMESTER

GAS ABSORPTION

1. Introduction

Gas absorption is an operation in which a gas mixture is contacted with a liquid for the purposes of preferentially dissolving one or more components of the gas and to provide a solution of them in the liquid. For example, the gas from by-product coke ovens is washed with water to remove ammonia and again with an oil to remove benzene and toluene vapors. Objectionable hydrogen sulfide is removed from such a gas or from naturally occurring hydrocarbon gases by washing with various alkaline solutions in which it is absorbed. Valuable solvent vapors carried by a gas stream can be recovered for reuse by washing the gas with an appropriate solvent for the vapors. Such operations require mass transfer of a substance from the gas stream to the liquid. When mass transfer occurs in the opposite direction, i.e. from the liquid to the gas , the operation is called desorption, or stripping. For example, the benzene and toluene are removed from the absorption oil mentioned above by contacting the liquid solution with stream, whereupon the vapors enter the gas stream and are carried away, and the absorption oil can be used again [1].

1.1. Equilibrium Solubility of Gases in Liquids

The rate at which a gaseous constituent of a mixture will dissolve in an absorbent liquid depends upon the departure from equilibrium which exists, and therefore it is necessary to consider the equilibrium characteristics of gas-liquid systems.

1.2. Ideal Liquid Solutions

When the liquid phase can be considered ideal, we can compute the equilibrium partial pressure of a gas from the solution without resort to experimental determination. In reality there are no ideal solutions, and actual mixtures only approach ideality as a limit.

When the gas mixture in equilibrium with an ideal liquid solution also follows the ideal-gas law, the partial pressure p^*_{AG} of a solute gas A equals the product of its vapor pressure p_A at the same temperature and its mole fraction in the solution X_A. This is given by Raoult's law.

$$p^*_{AG} = p_A X_A \qquad (1)$$

The asterisk is used to indicate equilibrium.

In an ideal solution all components, solvent and solute(s) alike-adhere to Raoult's law over the entire concentration range. In all dilute solutions in which there is no chemical interactions among components. Raoult's law applies to the solvent. This is true whether the solution is ideal or not. However, Raoult's law does not apply to the solute(s) in a dilute nonideal solution.

1.3. Nonideal Liquid Solutions

Pressure generally affects the solubility of a gas in a liquid much more than does temperature. The effect is always same: the solubility of gas increases as the gas temperature is increased. English chemist William Henry (1797-1836) proposed the generalization that the concentration (C) of a dissolved gas is proportional to the gas pressure (P_{gas}) of the solute.

$$C = HP_{gas} \qquad (2)$$

Equilibrium is reached between the gas and the dissolved gas within a liquid when the rates of evaporation and condensation of the gas molecules become equal. The rate of evaporation depends on the number of molecules of dissolved gas per unit volume of solution, and the rate of condensation depends on the number of molecules per unit volume in the gas in solution. To maintain equal rates of evaporation and condensation, as the number of molecules per unit volume increases in the gaseous state (through an increase in the gas pressure), the number of molecules per unit volume must also increase in the solution (through an increase in the gas concentration). When we apply Henry's law we assume that the gas does not react with the solvent. This assumption is valid in many cases [2].

1.4. Choice of Solvent for Absorption

When choice is possible preference is given to liquids with high solubility for the solute; a high solubility reduces the amount of solvent to be circulated. The solvent should be;

- Relatively nonvolatile
- inexpensive
- noncorrosive
- stable
- nonviscous
- nonfoaming
- preferably nonflammable

2. PACKED TOWERS

A common apparatus used in gas absorption and certain other operations is the packed tower, an example of which is shown in Fig. 1. The device consists of a cylindirical column, or tower, equipped with a gas inlet and distributing space at the bottom; a liquid inlet and distributor at the top; gas and liquid outlets at top and bottom, respectively; a liquid redistributor at the middle; and a supported mass of inert solid shapes, called "tower packing" (dumped packings). Packing materials are supplied large surface to contact the gas through the tower [3].

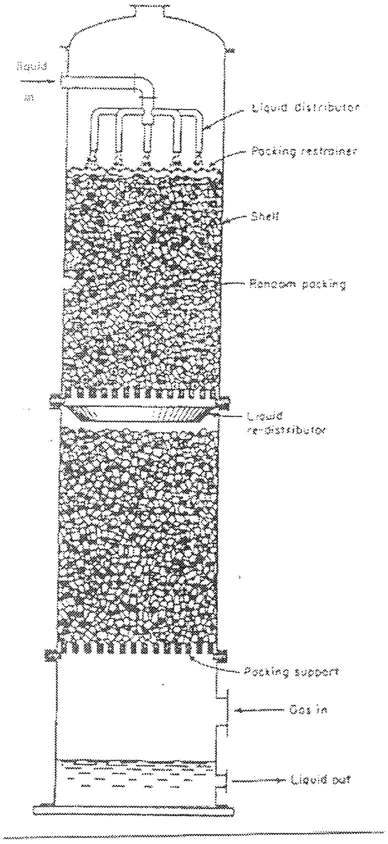


Figure 1. Packed Tower

2.1. Packing

Packing materials are tower packing, or fill, should offer the following characteristics:

1. Provide for large interfacial surface between liquid and gas. The surface of the packing per unit volume of packed space (a_p) should be large but not in a microscopic sense.

2. Posses desirable fluid-flow characteristics. This ordinarily means that the fractional void volume ε, or fraction of empty space, in the packed bed should be large. The packing must permit passage of large volumes of fluid through small tower cross sections without loading or flooding and with low pressure drop of gas.

3. Be chemically inert to fluids being processed. For example clay, porcelain, or various plastics could be used for packing materials.

4. Have structural strength to permit easy handling and installation.

5. Represent low cost.

Many kinds of tower packing have been invented and several tower packings are very widely used for the tower packing types are random and regular.

Random Packings

Random packings are simply dumped into the tower during installation and allowed to fall at random. Random packings most fequently used at present are Rashing rings (hollow cylinders), Lessing rings, Berl saddles, Intalox saddles, Pall ring; Tellerettes are shown in Fig. 2.

Regular Packings

These are of great variety. The counterflow trays already considered are a form of regular packing. The regular packings offer the advantages of low pressure drop and greater possible fluid flow rates, usually at the expense at least of more costly installation than random packings (Fig. 3).

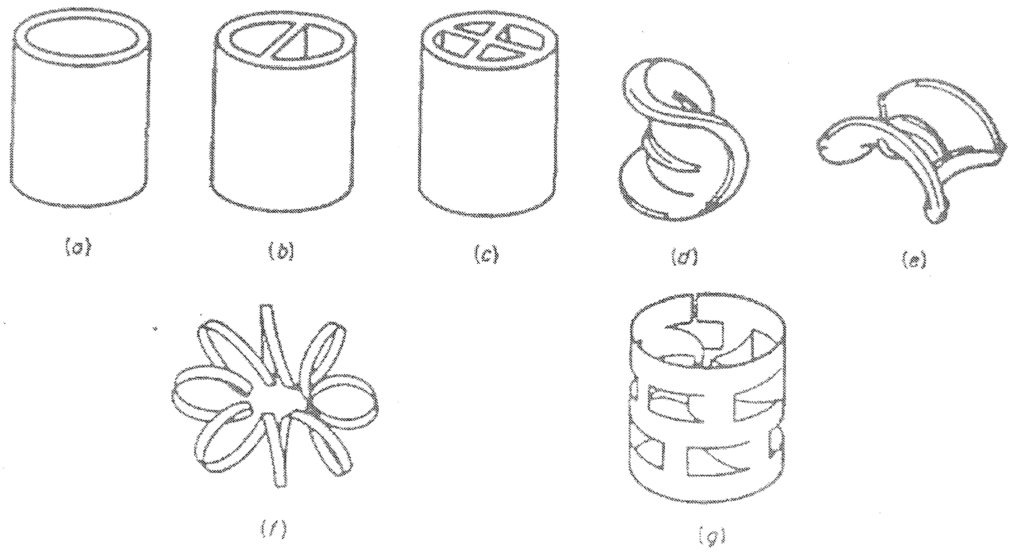


Figure 2. Some random tower packings: (a) Rasching rings, (b) Lessing ring, (c) partition ring, (d) Berl saddle, (e) Intalox saddle, (f) Tellerette and, (g) pall ring.

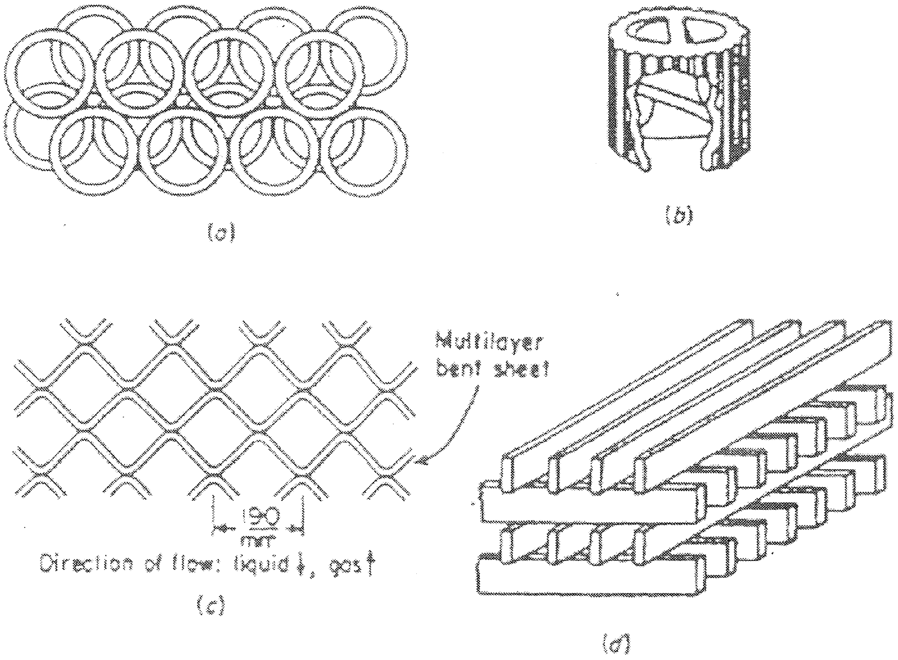


Figure 3. Regular or stacked packings: (a) Rashing rings stacked staggered (top view), (b) double spiral ring, (c) section through expanded-metal packing, (d) wood grids.

2.2. Packing Support

An open space at the bottom of the tower is necessary for ensuring good distribution of the gas into the packing. Consequently the packing must be supported above the open space. The support, must of course, be sufficiently strong to carry the weight of a reasonable height of packing, and it must have sample free area to allow for flow of liquid and as with a minimum of restriction.

2.3. Liquid Distribution and Redistribution

Uniform initial distribution of liquid at the top of the packed bed is essential for efficient column operation. This is accomplished by a device that spreads the liquid uniformly across the top of the packing. The requirement of good contact between liquid and gas is the hardest to meet, especially in large towers.

Ideally the liquid, once distributed over the top of the packing, flows in thin films over the entire packing surface all the way down the tower. Actually the films tend to grow thicker in some places and thinner in others, so that the liquid collects into small rivulets and flows along localized paths through the packing. Especially at the low liquid rates much of the packing surface may be dry or, at best, covered by a stagnant film of liquid. This effect is known as ***channeling***; it is chief reason for the poor performance of large packed tower. Channeling is much less pronounced provided the diameter of the individual packing pieces is smaller than at least one-eight the tower diameter. If the ratio of tower diameter to packing diameter is less than 8 to 1, the liquid tends to flow out of the packing, and down to walls of the column. In addition customary to provide for redistribution of the liquid at intervals varying from three to ten times the tower diameter but at least every 20 ft. With proper attention to liquid distribution, packed towers are successfully built to diameters of 20 ft or more (Fig 4).

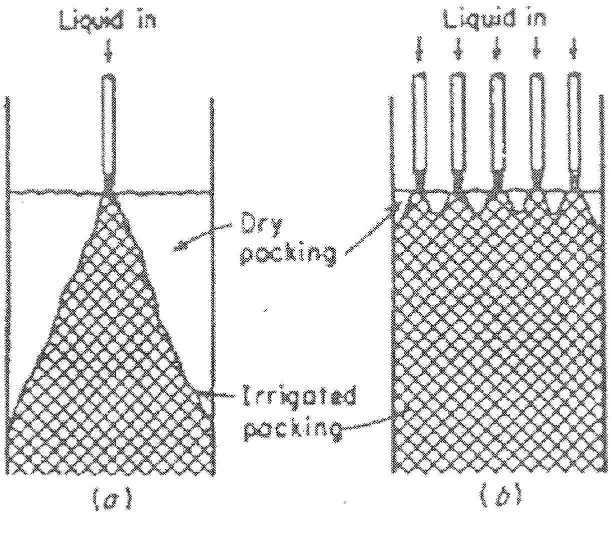


Figure 4. Liquid distribution and packing irrigation: (a) inadequate, (b) adequate

2.4. Countercurrent Flow of Liquid and Gas Through Packing

Pressure drop per unit packing depth comes from fluid friction. At a fixed gas velocity, the gas-pressure drop increases with increased liquid rate, principally because the reduced free cross section availed for flow gas resulting from the presence of the liquid [4].

In Fig. 5 shows pressure drop is plotted on logarithmic coordinates against the gas flow rate. When the packing is dry, the line so obtained is straight and has a slope of about 1.8. The pressure drop therefore increases with the 1.8^{th} power of the velocity (AB). If the packing is irrigated with a constant flow of liquid, the relationship between pressure drop and gas flow rate initially follows a line parallel to that for dry packing.

At higher liquid flow rates the effective open cross section is smaller because of the presence of liquid, and a portion of the energy of the gas stream is used to support an increasing quantity of liquid in the column (A′B′). For all liquid rates, a zone is reached where pressure drop is proportional to a gas flow rate power distinctly higher than 1.8; this zone is called the ***loading zone***, as indicated Fig. 5. The increase in pressure drop is due to the rapid accumulation of liquid in the packing void volume. If increase in gas velocity, the pressure drop rises even more rapidly, and the lines become almost vertical. In local regions of the column, the liquid becomes the continuous phase, and the ***flooding*** point has been reached. Higher gas flows can be used temporarily, but then liquid rapidly accumulates and the entire column may fill with liquid (C to C′). The flooding velocity depends strongly on the type and size of packing and the liquid mass velocity.

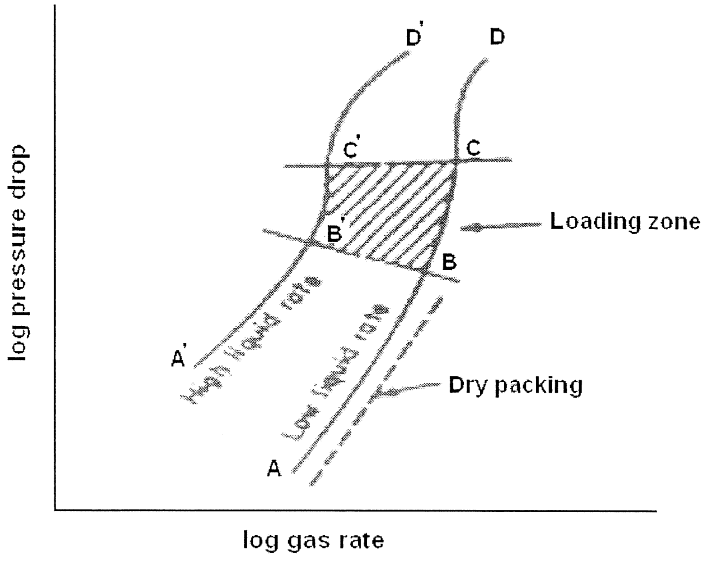


Figure 5. Pressure-drop characteristics of packed column

2.4.1. Loading and Flooding

Flooding conditions in random packings depend upon the method of packing (wet or dry) and settling of the packing. In a tower containing a given type and size of packing and being irrigated with a definite flow of liquid, there is an upper limit to the rate of gas flow called the ***flooding velocity***. Above this gas velocity the tower cannot operate. At low gas velocities the liquid flows downward through the packing, essentially uninfluenced by the upward gas flow. As the gas flow rate is increased at low gas velocities, the pressure drop is proportional to the flow rate to the 1.8 power. At a gas flow rate called the ***loading point***, the gas starts to hinder the liquid down flow, and local accumulations or pools of liquid start to appear in the packing. The pressure drop of the gas starts to rise at a faster rate. At the flooding point, the liquid can no longer flow down through the packing and is blown out with the gas. In an actual, operating tower, the gas velocity is well below flooding. The optimum economic gas velocity is about one-half or more of the flooding velocity. It depends upon an economic balance between the cost of power and the fixed charges on the equipment cost.

2.4.2. Pressure Drop

For simultaneous countercurrent flow of liquid and gas, the pressure drop data of various investigators show wide discrepancies due to differences in packing density and manufacture, such as changes in wall thickness. Estimates therefore cannot be expected to be very accurate. Several generalized correlations have been proposed for the pressure drop and flooding velocity in packed columns. Most of these use a log-log plot with $(G_x/G_y)(\rho_y/\rho_x)^{0.5}$ on the abscissa and a function containing G_y^2 on the ordinate. Fig. 6 gives correlations for estimating flooding velocities and pressure drops in packed towers. Usually the flow ratio G_x/G_y is known, and G_y can then be determined directly whereas trial-and-error solution is needed if G_y and G_x are on separate axes. In this Figure where G_x and G_y are in lb/ft^3, and g_c is 32.174 lb$_f$ft/(lb.s^2).

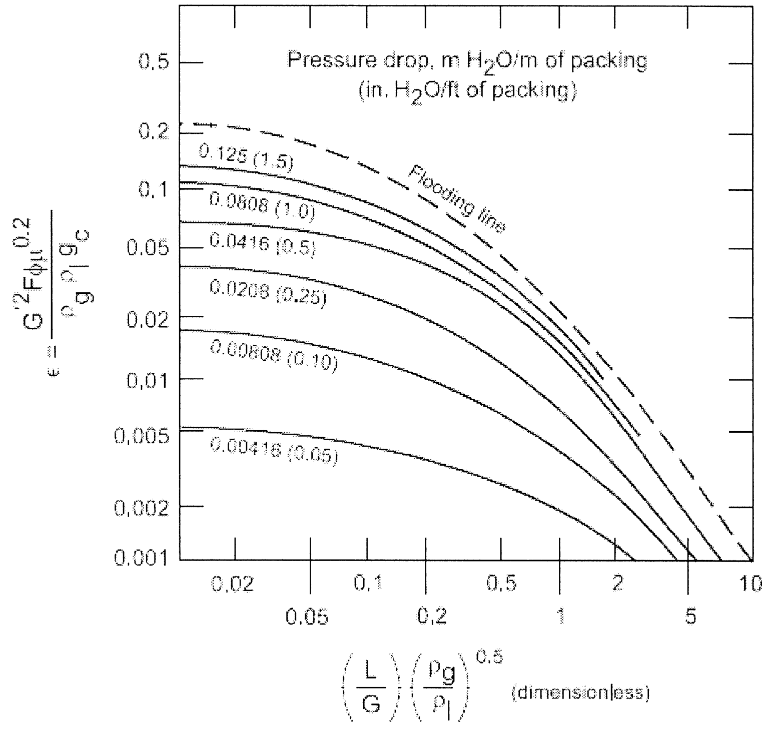


Figure 6. Generalized correlation for flooding and pressure drop in packed columns.

2.5. Material Balances For Packed Tower

For the case of solute A diffusing through a stagnant gas and then into a stagnant fluid, an overall material balance on component A in Fig.7 for a packed tower is

$$L'(\frac{x_2}{1-x_2}) + V'(\frac{y_1}{1-y_1}) = L'(\frac{x_1}{1-x_1}) + V'(\frac{y_2}{1-y_2}) \qquad (3)$$

Where L′ is kg mol inert liquid/s or kg mol inert liquid/s.m^2, V′ is kg mol inert gas/s or kg mol inert gas/s.m^2, and y_1 and x_1 are mole fractions A in gas and liquid, respectively. The flows L′ and V′ are constant throughout the tower, but the total flows L and V are not constant.

A balance around the dashed-line box in Fig. 7 gives the operating line equation:

$$L'(\frac{x}{1-x}) + V'(\frac{y_1}{1-y_1}) = L'(\frac{x_1}{1-x_1}) + V'(\frac{y}{1-y}) \qquad (4)$$

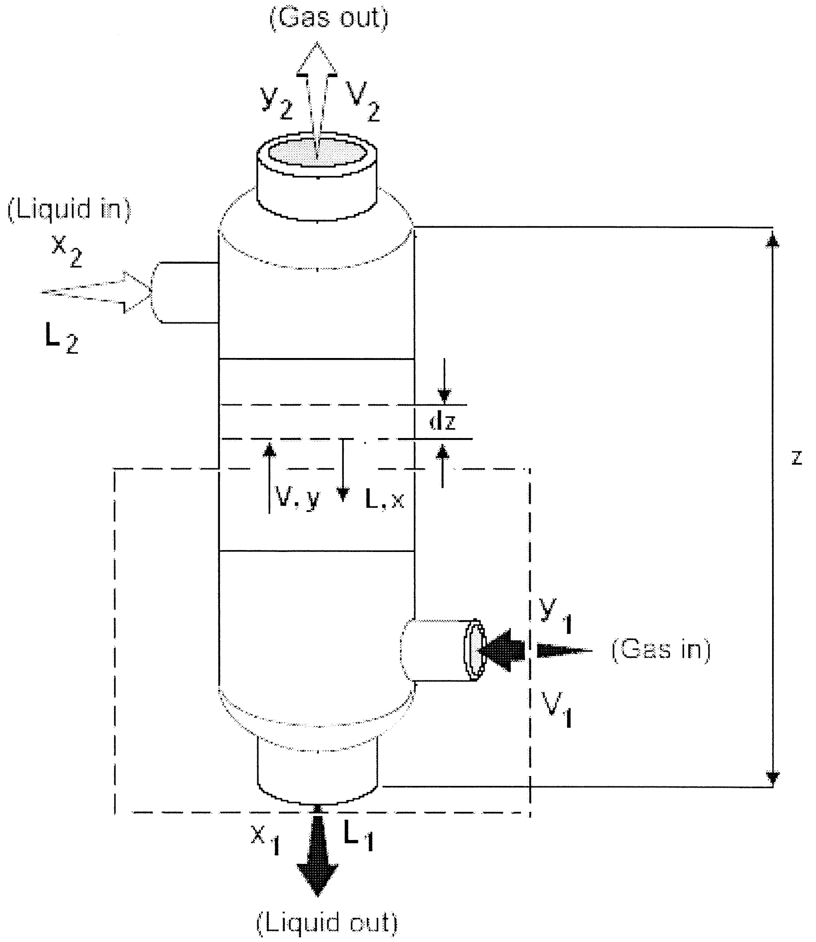


Figure 7. Material balance for a counterurrent packed absorption tower

3. INTERFACE MASS TRANSFER

3.1 Mass Transfer Between Phases

Transfer of material between phases is important in most separation processes in which gases and liquids are involved. The solute A was usually transferred from the fluid phase by convective mass transfer and through the solid by diffusion. In the present section we shall be concerned with the mass transfer of solute A from one fluid phase by convection and then through a second fluid phase by convection. For example, the solute may diffuse through a gas phase and then diffuse through and be absorbed in an adjacent and immiscible liquid phase. This occurs in the case of absorption of ammonia from air by water.

The two phases are in direct contact with each other, such as in a packed, tray, or a spray type tower, and the interfacial area between the phases is usually not well defined. In two-phase mass transfer, a concentration gradient will exist in each phase, causing mass transfer to occur. At the interface between the two fluid phases, equilibrium exists in most cases [5].

3.2. Concentration Profiles in Interface Mass Transfer

The most widely used model for describing the absorption process is the **two-film**, or **double-resistance**, theory, which was first proposed by Whitman in 1923. The two-film model starts by assuming that the gas and liquid phases are in turbulent contact with each other, separated by an interface area where they meet. This assumption may be correct, but no mathematical expressions adequately describe the transport of a molecule through both phases in turbulent motion. Therefore, the model proposes that a mass-transfer zone exists to include a small portion (film) of the gas and liquid phases on either side of the interface. The mass-transfer zone is comprised of two films, a gas film and a liquid film on their respective sides of the interface. These films are assumed to flow in a laminar, or streamline, motion. In laminar flow, molecular motion occurs by diffusion, and can be categorized by mathematical expressions. This concept of the two-film theory is illustrated in Fig. 8.

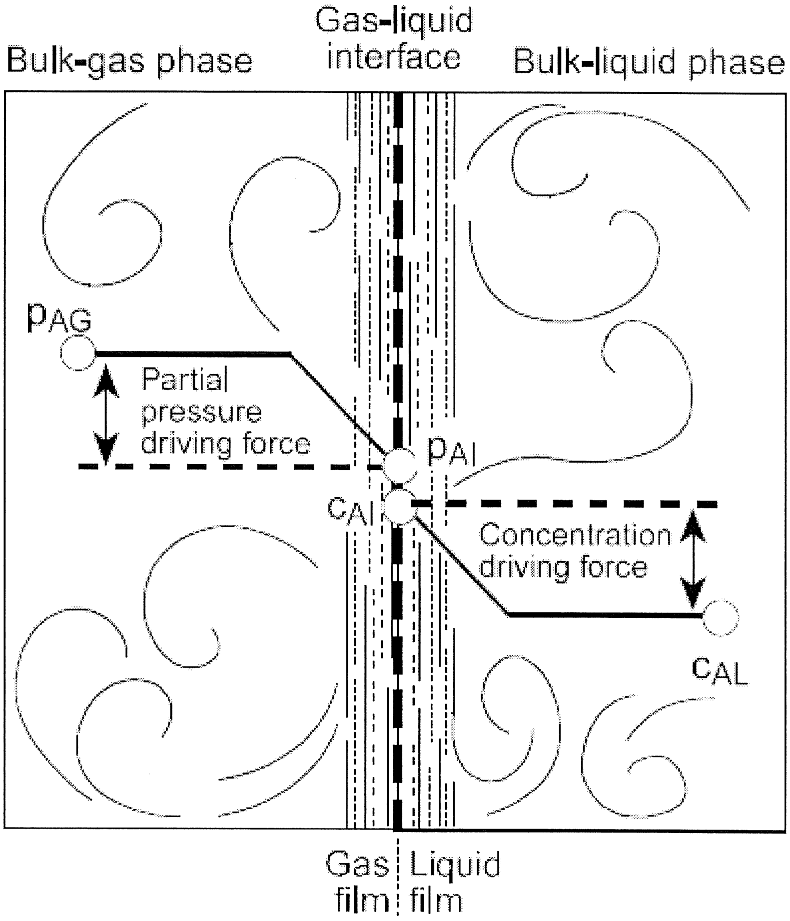


Figure 8. Visualization of two-film theory.

According to the two-film theory, for a molecule of substance A to be absorbed, it must proceed through a series of five steps. The molecule must:

1. Migrate from the bulk-gas phase to the gas film,
2. Diffuse through the gas film,
3. Diffuse across the interface,
4. Diffuse through the liquid film,
5. Mix into the bulk liquid.

The theory assumes that complete mixing takes place in both gas and liquid bulk phases and that the interface is at equilibrium with respect to pollutant molecules transferring in or out of the interface. This implies that all resistance to movement occurs when the molecule is diffusing through the gas and liquid films to get to the interface area, hence the name *double-resistance* theory. The partial pressure (concentration) in the gas phase changes from P_{AG} in the bulk gas to P_{AI} at the interface.

A gas concentration is expressed by its partial pressure. Similarly, the concentration in the liquid changes from C_{AI} at the interface to C_{AL} in the bulk liquid phase as mass transfer occurs. The rate of mass transfer from one phase to the other then equals the amount of molecule A transferred multiplied by the resistance molecule A encounters in diffusing through the films.

$$N_A = k_g (P_{AG} - P_{AI}) \tag{5}$$

$$N_A = k_l (C_{AI} - C_{AL}) \tag{6}$$

Where; N_A = rate of transfer of component A [gmol/(h.m^2)], k_g = mass-transfer coefficient for gas film, kmol/(s.m^2.kPa), k_l = mass-transfer coefficient for liquid film, kmol/(s.m^2.kPa), P_{AG} = partial pressure of solute A in the gas, P_{AI} = partial pressure of solute A at the interface, C_{AI} = concentration of solute A at the interface, C_{AL} = concentration of solute A in the liquid.

The mass-transfer coefficients, k_g and k_l, represent the flow resistance the solute encounters in diffusing through each film respectively (Fig. 9). The value for a mass transfer coefficient increases, the amount of pollutant transferred (per unit of time) from the gas to the liquid increases. An analogy is the resistance electricity encounters as it flows through a circuit.

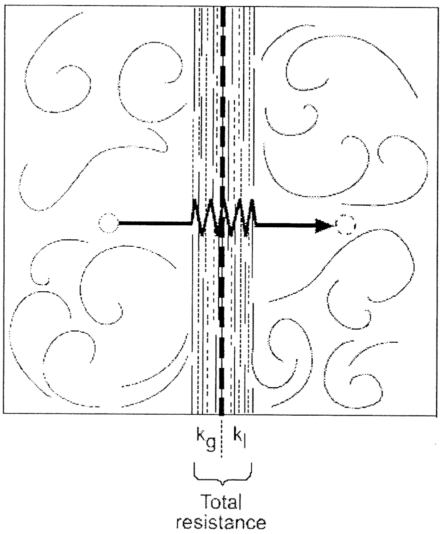


Figure 9. Resistance to motion encountered by a molecule being absorbed.

Equations 5 and 6 define the general case of absorption and are applicable to both curved and straight equilibrium lines. In practice, Equations 5 and 6 are difficult to use, since it is impossible to measure the interface concentrations, P_{AI} and C_{AI}. The interface is a fictitious state used in the model to represent an observed phenomenon. Using the interface concentrations in calculations can be avoided by defining the mass transfer system at equilibrium conditions and combining the individual film resistances into an overall resistance from gas to liquid and vice versa. If the equilibrium line is straight, the rate of absorption is given by the equations below:

$$N_A = K_{OG} (P_{AG} - P^*_A) \tag{7}$$

$$N_A = K_{OL} (C^*_A - C_{AL}) \tag{8}$$

Where; N_A = rate of transfer of component A, K_{OG} = overall mass-transfer coefficient based on gas phase, K_{OL} = overall mass-transfer coefficient based on liquid phase, P_{AG} = partial pressure of solute A in the gas, P^*_A= equilibrium partial pressure of solute A at operating conditions, C_{AL} = concentration of solute A in the liquid, C^*_A = equilibrium concentration of solute A at operating conditions.

An important fact concerning Equations 10 and 11 is that they impose an upper limit on the amount of solute that can be absorbed. The rate of mass transfer depends on the concentration departure from equilibrium in either the gas ($P_{AG} - P^*_A$) or liquid ($C^*_A - C_{AL}$) phase. The larger these concentration differences are, the greater the rate of mass transfer becomes. If equilibrium is ever reached ($P_{AG} = P^*_A$) and ($C^*_A = C_{AL}$) absorption stops and no net transfer occurs. Thus, the equilibrium concentrations determine the maximum amount of solute that is absorbed. At equilibrium, the overall mass-transfer coefficients are related to the individual mass transfer coefficients by the equations below.

$$\frac{1}{K_{OG}} = \frac{1}{\mathrm{k_g}} + \frac{\mathrm{H}}{k_l} \tag{9}$$

$$\frac{1}{K_{OL}} = \frac{1}{\mathrm{k_l}} + \frac{1}{H \ k_{gl}} \tag{10}$$

H is Henry's law constant (the slope of the equilibrium). Equations 9 and 10 are useful in determining which phase controls the rate of absorption. From Equation 9, if H is very small (which means the gas is very soluble in the liquid), then $K_{OG} \approx k_g$, and absorption is said to be **gas-film controlled**. The major resistance to mass transfer is in the gas phase. Conversely, if a gas has limited solubility, H is large, and Equation 10 reduces to $K_{OL} \approx k_l$. The mass-transfer rate is **liquid-film controlled** and depends on the solute's dispersion rate in the liquid phase. Most systems in the air pollution control field are gas-phase controlled since the liquid is chosen so that the solute will have a high degree of solubility.

3.3. Mass Transfer Coefficients

The mass transfer coefficient is defined as the ratio of the molal flux, N_A to the concentration driving force. This is defied by equations of the form;

Flux = (coefficient) (concentration difference)

For example, gas-phase mass transfer rates may be defined as;

$$N_A = k_G(y_{AG} - y_{Ai}) = k_G'(p - p_i) \tag{11}$$

Where units (SI) of k_G are kmol/[(s.m^2)(mole fraction)], the units of k_G' are kmol/[(s m^2)(kPa)].

In a similar way, liquid phase mass-transfer rates may be defined by the relations;

$$N_A = k_L(x_{Ai} - x_{AL}) = k_L'(c_i - c) \tag{12}$$

Where units (SI) of k_L are kmol/[(s m^2)(mole fraction)], the units of k_L' are kmol/[(s m^2)(kmole/m^3)] or meters per second.

The individual film mass-transfer coefficient k_G and k_L depend generally upon Schmidt number, Reynolds number, and the size and shape of the packing. The interactions among these factors are quite complex. Hence, the correlations for mass-transfer coefficients are highly empirical. On the basis of the study (Sherwood and Holloway 1940), the liquid-film coefficient was found a function of liquid rate but was independent of gas rate up to the loading point. The experimental results from a number of random packing were represented by the equations;

$$\frac{k_L a_p}{D_l} = \alpha\left(305\frac{L}{\mu_l}\right)^{1-n}\left(\frac{\mu_l}{\rho_l D_l}\right)^{0.5} \tag{13}$$

Where; k_L = liquid phase mass transfer coefficient for dilute system, a_p= specific surface area of packing, D_l=diffusion coefficient of liquid.

Generalization of mass-transfer data for the gas phase has been much less successful than it has been for the liquid phase. Principal deterrents to the development of a general relationship have been the variation of effective area as a function of flow rates and surface tension and the lack of a gas-phase controlling test system unencumbered by side effects of heat development or chemical reaction.

Investigation of the behavior of gas films have been conducted with

1. Vaporization of pure liquids into a gas stream.
2. Absorption of a solute gas into a liquid offering a high degree of solubility.
3. Absorption of a solute gas into a liquid where the equilibrium partial pressure is zero because of an irreversible chemical reaction.

Onda, Takeuchi, and Okumoto correlated available gas-phase absorption data with the dimensionless equation

$$\frac{k_g RT}{a_t D_g} = C_1\left(\frac{G}{a_t \mu_g}\right)^{0.7}\left(\frac{\mu_g}{\rho_g D_g}\right)^{1/3}\left(a_t D_p\right)^{-2.0} \tag{14}$$

The overall mass transfer coefficients are calculated according to the following equations;

$$\frac{1}{K_G a_p} = \frac{1}{k_G a_p} + \frac{m}{k_l a_p} \tag{15}$$

$$\frac{1}{K_L a_p} = \frac{1}{k_L a_p} + \frac{1}{m k_G a_p} \tag{16}$$

Where; a_t=total surface area, D_g= diffusion coefficient of gas, D_p=diameter of packing, m =slope of the equilibrium curve.

3.4. HTU (Height of Transfer Units)

Frequently the values of the individual coefficient of mass transfer are so strongly dependent on flow rates that the quantity obtained by dividing each coefficient by the flow rate of the phase to which it applies is more nearly constant than the coefficient itself. The quantity obtained by this procedure is called the height equivalent to one transfer unit, since it expresses in terms of a single length dimension the height of apparatus required to accomplish a separation of standard difficulty.

The following relations between the transfer coefficients and the values of apply:

$$H_G = G_M / k_G a y_{BM} \tag{17}$$

$$H_{OG} = G_M / K_G a y^o{}_{BM} \tag{18}$$

$$H_L = L_M / k_L a x_B \tag{19}$$

$$H_{OL} = L_M / K_L a x^o{}_{BM} \tag{20}$$

The equations that express the addition of individual resistance in terms of HTU's applicable to either dilute or concentrate systems, are

$$H_{OG} = \frac{y_{BM}}{y^o{}_{BM}} H_G + \frac{mG_M}{L_M} \frac{x_{BM}}{y^o{}_{BM}} H_L \tag{21}$$

$$H_{OL} = \frac{x_{BM}}{x^o{}_{BM}} H_L + \frac{L_M}{mG_M} \frac{x_{BM}}{x^o{}_{BM}} H_G \tag{22}$$

These equations are strictly valid only when m, the slope of the equilibrium curve, is constant.

Where; L_M=molar liquid-phase mass velocity, G_M=molar gas phase mass velocity H_G, H_L=height of transfer units based on gas and liquid phase resistance, respectively, H_{OG}, H_{OL}=height of overall gas and overall liquid phase mass transfer units respectively, x_{BM}=logarithmic-mean inert-solvent concentration between bulk-liquid and interface values, $x^o{}_B$ = logarithmic-mean inert-solvent concentration between bulk-liquid value and value in equilibrium with bulk gas, y_{BM}=logarithmic-mean inert-solvent concentration between bulk-gas and interface values, $y^o{}_{BM}$ =logarithmic-mean inert-solvent concentration between bulk-gas value and value in equilibrium with bulk liquid.

3.4. NTU (Number of Transfer Units)

The NTU required for a given separation is closely related to the number of theoretical stages or plates required to carry out the same operation in a stage-wise or plate-type apparatus. For equimolal countercurrent diffusion, such as in a binary distillation, the number of overall gas-phase transfer units N_{OG} required for changing the composition of the vapor stream y_1 to y_2 is

$$N_{OG} = \int_{y_2}^{y_1} \frac{dy}{y - y^o} \tag{23}$$

When diffusion is in one direction only, as in the absorption of a soluble component from an insoluble gas,

The total height of packing required is then

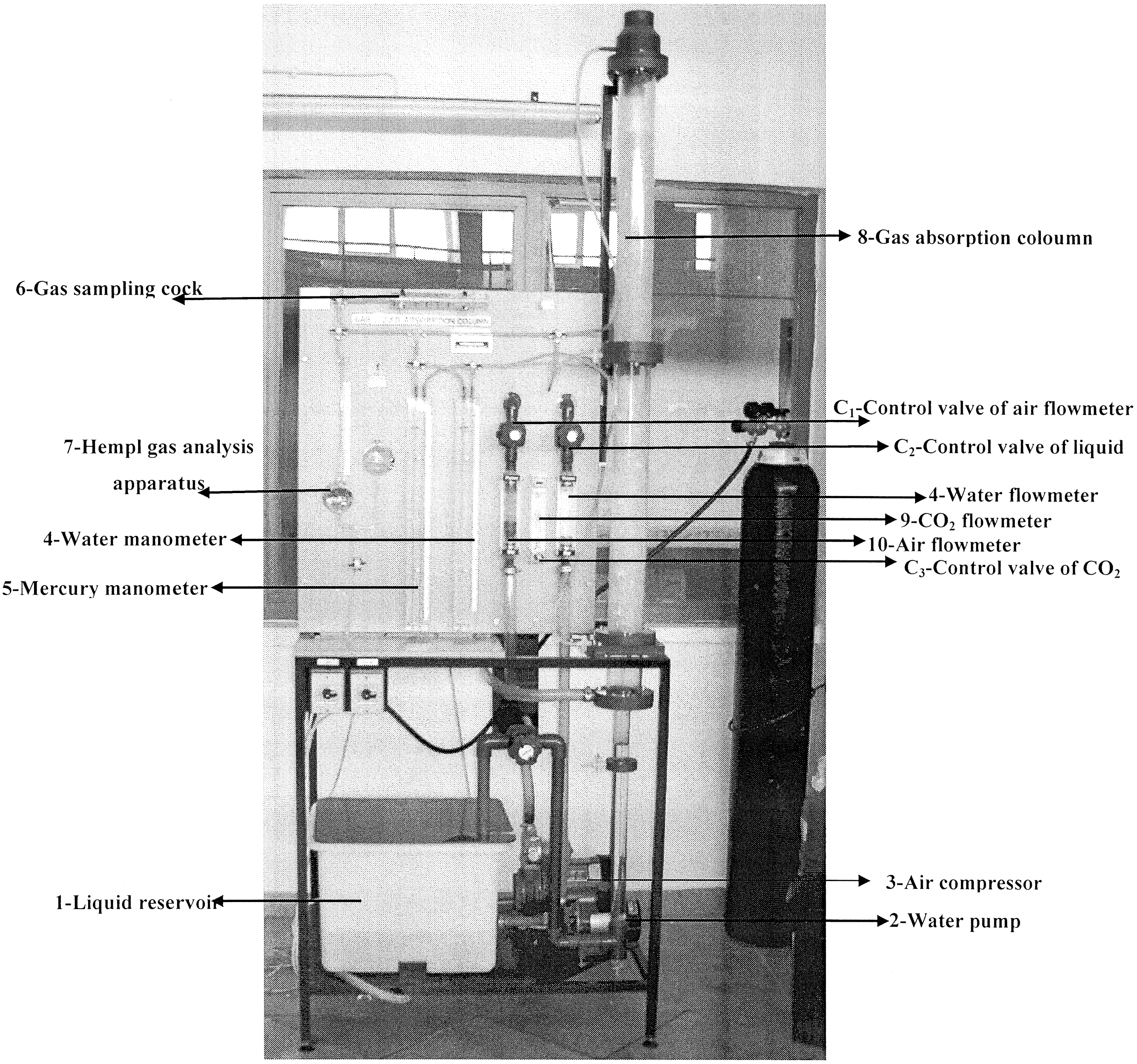
$$h_T = H_{OG} N_{OG} \tag{24}$$

When it is known that H_{OG} varies appreciably within the tower, this term must be placed inside the integral in Eq. 23 and 24 for accurate calculations of h_T. For example, the packed-tower design equation in terms of the overall gas-phase mass transfer coefficient would then be expressed as follows:

$$h_T = \int_{y_2}^{y_1} \left[\frac{G_M}{K_G a y^o_{BM}} \right] \frac{y^o_{BM}}{(1 - y)(y - y^o)} dy \tag{25}$$

4. EXPERIMENTAL SET UP

4.1. Description of Apparatus



4.2. Experimental Procedure

Section A-Dry Column

- Start the air compressor (3) and change the air flowmeter (10) 10 to 100 liters/minute with gas flow control valve C_2.
- Measure pressure drop with U manometer (4) at different gas flow rate.

Section B-Dry Column

- Start the air compressor (3) and the liquid pump (2).
- Change the air flowmeter (10) 10 to 100 liters/minute with gas flow control valve C_1 at least for five different liquid flow rate.
- Measure pressure drop with U manometer (4).

Section C-Gas Absorption

i. **To measure the absorption of carbon dioxide into water using the gas analysis equipment provided.**

- Start the liquid pump and adjust the water flow thought the column to approximately 6 liters/minute on flowmeter (4) by adjusting control valve C_2.
- Start the compressor and adjust control valve C_1 to give an air flow of approximately 20 liters/minute in flowmeter (9).
- Carefully open the pressure regulating valve on the carbon dioxide cylinder, and adjust valve to give a value on the flowmeter (9) approximately quarter of the air flow. Ensure the liquid seal at the base of the absorption column is maintained by, if necessary, adjustment of control valve C_3
- After 15 minutes or so of steady operation, take samples of gas simultaneously from sample top of the column. Analyze these consecutively for carbon dioxide content in these gas samples as shown in the accompanying sketch and following notes (Appendix II step A).
- Flush the sample lines by repeated sucking from the line, using the piston and expelling the contents of the cylinder to atmosphere. Note that the volume of the cylinder is about 100 cc. Estimate the volume of the tube leading to the device. Then decide how many times you need to suck and expel (Appendix II, step B and C).

- With the absorption globe isolated and the vent to atmosphere closed, fill the cylinder from the selected line by drawing the piston out slowly (AppII, step B). Note volume taken into cylinder V1, which should be approximately 20 mL for this particular experiment. Wait at least two minutes to allow the gas to come to the temperature of the cylinder.
- Isolated the cylinder from the column and the absorption globe and vent the cylinder to atmosphere again.
- Connect cylinder to absorption globe. The liquid level should not change. If it does change, briefly open to atmosphere again.
- Wait until the level in the indicator tube is on zero showing that the pressure in the cylinder is atmospheric.
- Slowly close the piston to empty the cylinder into the absorption globe. Slowly draw the piston out again (App. II, step E and F).

ii. To calculate rate of absorption of carbon dioxide into water from analysis of liquid solutions

- Start the liquid pump and adjust the water flow throughout the column to approximately 6 liters/minute on flowmeter (4) by adjusting control valve (C_2).
- Start the compressor and adjust control valve C_1 to give an air flow of approximately 20 liters/minute in flowmeter (10).
- Carefully open the pressure regulating valve on the carbon dioxide cylinder, and adjust valve to give a value on the flowmeter (9) approximately quarter of the air flow. Ensure the liquid seal at the base of the absorption column is maintained by, if necessary, adjustment of control valve C_3.
- After 15 minutes of steady operation, take samples from liquid tank and column exit valve. Analyze the samples according to the procedure detailed in calculations.

4.3. Calculations

Section A-Dry Column

- Calculate gas mass flux (G_{air}) and pressure drop (ΔP) for different gas flow rates.
- Plot gas mass flux (G_{air}) vs. pressure drop.

Section B-Wet Column

- Calculate gas mass flux (G_{air}), liquid mass flux (L_{liq}) and pressure drop (ΔP) for different gas and liquid flow rates.
- Plot gas mass flux (G_{air}) vs. pressure drop.
- Calculate flooding flow rate of gas each liquid flow rate.
- Calculate optimum gas flow rate and corresponding pressure drop.

Section C-Gas Absorption

i. To measure the absorption of carbon dioxide into water using the gas analysis equipment provided.

- Calculate the amount of CO_2 absorbed in column from analysis of samples at inlet and outlet

  From Hempl apparatus, volume fraction of CO_2 in inlet gas stream;

$$Y_i = \left(\frac{F_{CO_2}}{F_{CO_2} + F_{air}} \right)_i \tag{26}$$

  and outlet;

$$Y_o = \left(\frac{V_2}{V_1} \right)_o \tag{27}$$

  If F_a is liters/second of CO_2 absorbed between top and bottom, then;

$$[F_{CO_2} + F_{air}]Y_i - [F_{CO_2} + (F_{air} + F_a)]Y_o = F_a \tag{28}$$

- Calculate the G_a (g. moles/second)

$$G_a = \left(\frac{F_a}{22.42} \right) \left(\frac{\text{av. column pressure mmHg}}{760} \right) \left(\frac{273}{\text{av. column temp.}(^\circ C) + 273} \right) \tag{29}$$

Absorbed CO_2 : ....

g. moles/second:..................

- Calculate the individual liquid and gas sides mass transfer coefficients.
- Calculate the overall liquid and gas sides mass transfer coefficients.

iii. To calculate rate of absorption of carbon dioxide into water analysis of liquid solutions

- Calculate the amount of free CO_2 in the water

$$\text{g.mole/liter of free } CO_2 = \frac{V_{\text{titrant}} \times 0.0277}{\text{ml. of sample}} \qquad (30)$$

- Determine theoretical column performance.
- Compare your experimental findings with the values calculated theoretically and discuss your results.

5. SYMBOLS

a :Effective interfacial mass-transfer area per unit volume of tower of apparatus, m^2/m^3

a_p : Specific surface area of packing, m^2

a_t : Total surface area, m^2

C : Concentration of dissolved gas, g mole/ m^3

C_l : Constant

C_{AL} : Concentration of solute A in the liquid, kmol/ m^3

C^*_A : Equilibrium concentration of solute A at operating conditions, kmol/ m^3

D_g, D_l : Diffusion coefficient of gas and liquid, respectively, m^2/s

D_p : Diameter of packing, m

F_a : CO_2 absorbed between top and bottom, m^3/s

F_{air}, F_{CO2} : Volumetric flow rate of CO_2 and air, respectively, m^3/s

F_p : Packing factor

G : Gas phase mass velocity, kg/s

G_x, G_y : Mass velocity for liquid and gas stream, respectively, kg/s

G_M : Molar gas phase mass velocity, kmol/s

g_c : The proportionality factor for Newton's Law

h_T : Total height of tower packing required, m

H : Henry's law constant, $Pa.m^3/kmol$

H_G, H_L : Height of transfer units based on gas and liquid phase resistance, respectively

H_{OG}, H_{OL} : Height of overall gas and overall liquid phase mass transfer units, respectively

k_G, k'_G : Gas phase mass transfer coefficient for dilute system, kmol/[(s m^2)(mole fraction)], kmol/[(s m^2)(kPa)]

k_L, k'_L : Liquid phase mass transfer coefficient for dilute system, kmol/[(s m^2)(mole fraction)], kmol/[(s m^2)(kPa)]

K_G : Overall gas-phase mass transfer coefficient for dilute system

K_{OG} : Overall mass-transfer coefficient based on gas phase

K_L : Overall liquid-phase mass transfer coefficient for dilute system

K_{OL} : Overall mass-transfer coefficient based on liquid phase

L' : Molar flow rate of inert liquid, kmol/s

L_M : Molar liquid-phase mass velocity, kmol/s

m : Slope of the equilibrium curve

N_A : Interface mass-transfer rate of solute A per unit interfacial area, kmol/m^2.s

N_G, N_L : Number of transfer units for gas and liquid-phase, respectively

N_{OG}, N_{OL} : Number of overall gas and liquid-phase mass transfer units, respectively

n : Constant

P_A : Vapor pressure of A, Pa

P_{AG} : Partial pressure of solute A in the gas, Pa

P^*_{AG} : Equilibrium partial pressure of solute A at operating conditions, Pa

P_{gas} : Gas pressure of a solute, Pa

ΔP : Pressure drop, Pa

R : Gas constant, Pa.m^3/kmol.K

T : Temperature, K

V' : Molal flow rate of inert gas, kmol/s

x : Mole fraction of solute in liquid

x_{AL} : Mole fraction of solute in bulk liquid phase

x_{Ai} : Mole fraction of solute in liquid at gas-liquid interface

x^o : Mole fraction of solute in bulk liquid in equilibrium with bulk gas solute concentration y

x_{BM} : Logarithmic-mean inert-solvent concentration between bulk-liquid and interface values

x^o_{BM} : Logarithmic-mean inert-solvent concentration between bulk-liquid value and value in equilibrium with bulk gas

y : Mole fraction of solute in gas

y_{AG} : Mole fraction of solute in gas at gas-liquid interface

y^o : Mole fraction solute in bulk gas in equilibrium with bulk-liquid solute concentration z

y_{BM} : Logarithmic-mean inert-solvent concentration between bulk-gas and interface values

y^o_{BM} : Logarithmic-mean inert-solvent concentration between bulk-gas value and value in equilibrium with bulk liquid

α : Constant

ε : Void fraction of dry packing

μ_g, μ_l : Viscosity of gas and liquid, respectively, Pa.m

ρ_g, ρ_l : Average molar density of gas and liquid-phase, kg/m^3

6. REFERENCES

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3. 3. W. L. McCabe, J. C. Smith, P. Harriot, 'Unit Operations of Chemical Engineering', 5rd ed., McGraw Hill, New York, 1993.
4. C. J. Geankoplis, 'Transport Processes and Unit Opeartions', 2nd ed., Allyn and Bacon INC., Boston, 1983.
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APPENDIX-I

Group Number:

Name Surname:

Date:

I. DRY COLUMN

Air (L/min)	10	20	30	40	50	60	70	80	90	100
ΔP (mmH_2O)										

II. WET COLUMN

Air (L/min)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Water (L/min)										
1										
3										
5										
7										
9										

III. GAS ABSORPTION

t (min)	**$V_{titrant}$ (mL) for C_{tank}**	**$V_{titrant}$ (mL) for C_{exit}**	**V_{CO2} (mL)**
0			
15			
30			
45			
60			

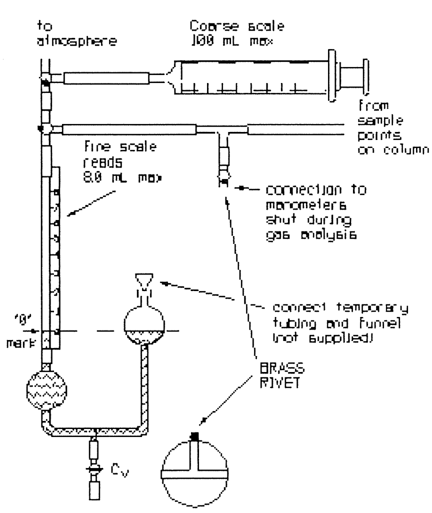
$F_{Air:}$: (L/min) $V_{gas\ sample}$= (mL) $(\Delta P)_I$ = (mm H_2O)

F_{CO2}: (L/min) $V_{liquid\ sample}$= (mL) $(\Delta P)_O$ = (mm H_2O)

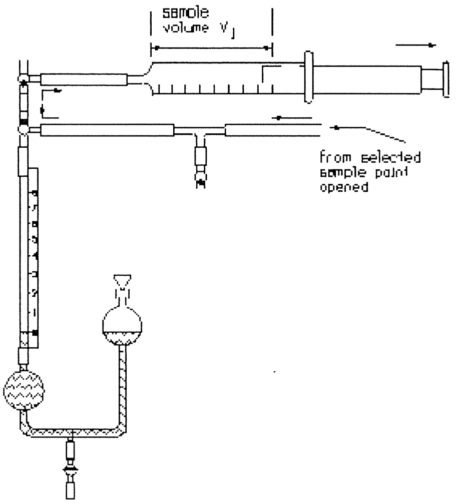
F_{H2O}: (L/min)

APPENDIX-II

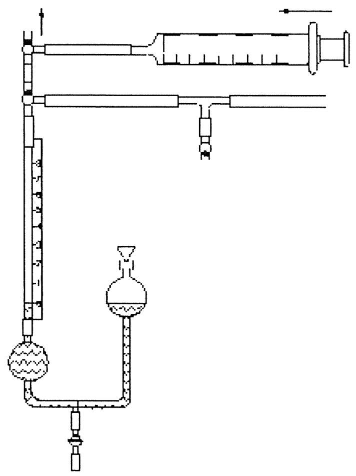
HEMPL APPARATUS



Ⓐ FILL WITH STANDARD REAGENT TO '0' ON SCALE



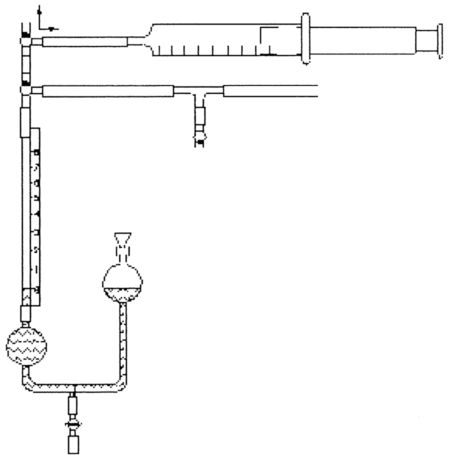
Ⓑ TAKING GAS SAMPLE



Ⓒ DISCHARGING TO ATMOSPHERE

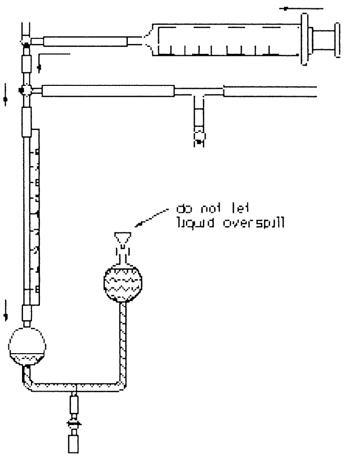
repeat Ⓑ and Ⓒ to remove unrepresentative gas from sample lines.

Then take true sample by further repeating step Ⓑ to selected volume V_1.



Ⓓ VENTING TO ATMOSPHERE

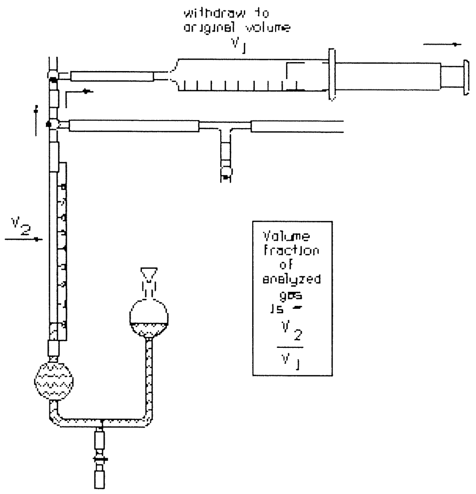
(balancing pressures)



Ⓔ CHARGING HEMPL APPARATUS

repeat Ⓔ and Ⓕ slowly until

V_2 is constant



Ⓕ WITHDRAWING GAS SAMPLE AND TAKING READING V_2