



Chapter II

LITERATURE REVIEWS AND THEORETICAL CONSIDERATION

2.1 Adsorbent

It has long been known that adsorbent is a porous solid that can take up relatively large volumes of adsorbate, condensable gas or solute in solution (1). It has the property of adsorbing several times its own volume of various gases. The two factors, surface area and porosity of adsorbent are now recognized to play complementary parts in adsorption phenomena. Mantell (2) stated the commercially important solid adsorbents, in order of their tonnage consumed, as shown in table 2.1

Table 2.1

Industrial Adsorbents

Adsorbent	Important Industrial Uses
Fuller's earth	Refining of petroleum fractions, vegetable and animal oils and fats, and waxes.
Bauxite	Percolation treatment of petroleum fractions; dehydration of gases.
Acid-treated clays.....	Contact filtration of petroleum fractions.

Adsorbent	Important Industrial Uses
Bone char or bone black...	Sugar refining; ash removal from solution.
Decolorizing carbons and water carbons.....	Sugar refining; refining of vegetable and animal oils and fats and of waxes; miscellaneous decolorizing of inorganic and organic substances; water purification; purification of dry-cleaning fluids; purification of food products.
Gas adsorbent carbon.....	Solvent recovery; recovery of gasoline from natural gas; elimination of industrial odors purification of carbon dioxide and industrial gases; gas masks.
Alumina.....	Dehydration of air, gases and liquids.
Silica gel.....	Dehydration and purification of air and industrial gases; air conditioning; refining of petroleum distillates; gas masks.
Base-exchange silicates...	Water treatment.
Magnesia.....	Treatment of gasoline and regenerating of dry cleaning solvents

Adsorbent	Important Industrial Uses
Medicinal carbons.....	Elimination of bacteria and tonic poisons; an addition to animal foods.
Metal-adsorbent chars....	Recovery of precious metals.

For classification (3) of adsorbent basing on their physical structure, it can be grouped into 2 types, powdered and granular type. Large surface area of powdered type plays important role in adsorption process. For granular type, Broekhoff, J.C.P., and Linsen, B.G., (4) obtained that the specific surface area alone is not sufficient to characterize adsorbent. For a study of the accessibility to the surface, the shape and dimensions of the pores present in the matrix should be known. Porous substance may be divided into at least two sub-groups, macroporous and microporous. Russel, S. (5) distinguished between macropores and micropores by fixing the borderline in that case at a pore diameter of 0.005 mm. (5 μ)

Wicke (6) determined the volume of the macropores and micropores of charcoal and Silica gel by using adsorption isotherm of benzene, and he assumed that the surface area within the pores is given by

$$S = \frac{2.5 V_p \cdot 10^4}{r_p} \quad (2.1)$$

Where S = specific surface area m^2/gm
 V_p = specific pore volume cm^3/gm
 r_p = the mean pore radius in \AA

Wicke obtained values varying between 0.9 and $1.5 m^2/gm$ for the surface area in the macropores and figures between 350 and $1,700 m^2/gm$ for the surface area in the micropores. The result of this study thus indicated that the surface area available in macropores is negligible in comparison with that in the micropores. He concluded that surface area available for adsorption of molecules could be determined by the surface area in the micropores. Nevertheless, macropores play an important role in the operational use of the adsorbent, since the rates of adsorption depend largely on the rate of diffusion in the pores.

Broekhoff and Lisen (4) added that it is necessary to have adsorbents with large specific surface area. A large specific surface area can hardly be obtained by grinding. They stated that grinding to a size of 1μ results in raising the specific surface area to about $1 m^2/gm$. For the desired specific surface area vary from 10 to over $500 m^2/gm$, other methods have to be used to prepare microporous substance such as precipitation, thermal decomposition, leaching and sublimation.

Il'in and Neimark (7) gave a brief survey of the most widely used methods for modifying the properties of zeolites

used at the synthesis stage and during special treatment of crystals already formed. Several new methods have been suggested for the directed modification of the properties of synthetic zeolites, namely: hydrothermal crystallization in the presence of small amount of impurities, production of mixed adsorbents of the type of zeolite amorphous aluminosilicate by interrupting the crystallization at different stages, modification of the dehydration process of zeolites, modification of the geometrical parameters of structure and localization of cations in zeolites during adsorption.

Slinyakova and Kurennaya (8) synthesized silico-polyvinylsiloxanes, new mixed adsorbent by combined hydrolytic polycondensation of triethoxyethylsilane and vinyltriethoxysilane with subsequent formation of gels of the reaction products. A decrease in the content of vinyl groups reduces the time of formation of mixed gels, and favors the production of porous structures with a small effective radius of the pores.

Van de Plas (9) remarked that activated carbon is the mostly used for removal of impurities in industrial work for following reasons.

1. The ease with which carbon is formed from its compounds, especially many cheap and abundant natural products, by heating them in the absence of air
2. The difficulty of crystallization of carbon
3. Active surface area (4) for the more common com-

mercial activated carbons vary from 500 to 1,400 m^2/gm

4. The carbon can periodically be reactivated to restore its adsorbate removal capacity so that it can be repeatedly reused.

According to Hashimoto, Miura, Yoshikawa and Imai (10) activated carbon is used in adsorption processes for solvent recovery, gas separation, odor removal, and so on. Recently the need for activated carbon has considerably increases, especially with regard to waste water treatment. Activated carbon is manufactured from various raw materials such as coal, wood, coconut shell, bone, resin etc. The main steps in the production of activated carbon are carbonization and activation. The carbonization step is usually performed in an inert atmosphere to remove volume of material. The activation step is a mild oxidation with such oxidizing gases as steam, CO_2 or air to develop an efficient pore structure.

Kawahata and Walker (11) activated an anthracite with CO_2 using fluidized bed reactor and they studied extensively the changes of pore characteristics such as surface area, pore volume and pore volume distribution. They also investigated the adsorption capacity of activated anthracites for CCl_4 and concluded that the optimum percentage of burnoff was 53.4%.

For the comparison of two types of activated carbon, powdered and granular type, Mantell (2) stated that granular

activated carbons which are mechanically strong, relative dense and highly active are required for industrial adsorption, as purpose the soft, finely pulverized, highly porous and generally effective active decolorizing carbons are practically worthless.

Granular activated carbons have been used since 1940 for dextrose production and in 1950 for cane sugar production (12). Now it can be used widely for chemical industry pharmaceutical industry and water treatment. Granular activated carbon, used in properly-designed system employing modern equipment and techniques, offers many benefits include (13) a clean, continuous operation; counter-current efficiency leading to higher impurity loading on the carbon and thus lower carbon usage; less product loss due to filter cake retention, improved product quality and the possibility of carbon regeneration. Economic consideration (12) of powdered activated carbon and granular one was illustrator in Table 2.2

Table 2.2

Operating Cost/Ton of Glucose in U.S. Dollars

	Pulverized System	Granular System
Carbon	2.88	0.31
Filter aid	0.45	0.04
Labor	1.05	0.21

	Pulverized System	Granular System
Glucose loss	0.29	0.11
Regeneration	-	0.38
Miscellaneous	0.76	0.25

(Miscellaneous includes : sweetening-off, evaporation maintenance-handling etc.)

2.2 Adsorption

2.2.1 Equilibrium Adsorption

According to Mantell (2) adsorption concerns itself with the concentration, as the result of surface forces existing on a solid, of gases, vapors, liquids or solutes. Adsorption may be defined in terms of a unit operation in the chemical engineering sense as that operation which deals primarily with the utilization of surface forces and the concentration of materials on the surfaces of solid bodies referred to as adsorbent.

Adsorption is usually explained (3) in terms of the surface tension or energy per unit area of the solid. The adsorption is termed "physical" for the relatively weak and are called Van de Waal's forces involved, and the adsorbed molecules are easily released from the surface. In contrast to this, stronger forces and irreversible process involved

is known as chemisorption, absorption. The molecules adsorbed in this case are recovered in the form of compounds containing atoms of adsorbent.

Mantell (2) added that adsorption should take place with the evolution of heat for it invariably decreases with rise in temperature. The heat of adsorption is defined as the decrease in the heat content of the system which its magnitude serves as a clue as to the nature of the forces involved and may be used to distinguish in some degree between physical adsorption and chemisorption as shown in Table 2.3 (2)

Table 2.3

Heat of Physical Adsorption and Chemisorption

	Physical Adsorption cal/mole	Chemisorption cal/mole
Nitrogen (14) on iron catalyst	2,000-3,000	-
Oxygen (15) on charcoal	3,700 at 150°C	70,000-4,000 at room temp.
Hydrogen (16) on zinc oxide	1,900 at 0°C	20,000 at 300-400°C

Adsorption may be defined as the accumulation of dissolved particles from a solvent on to the surface of an

adsorbent. According to Tabbutt and Bahiah (17), adsorption capacity is defined as the mass of solute adsorbed on the surface of a given mass of adsorbent. Peterson and Lee (18) pointed out that the results of laboratory data on the sorption of a fluorescent dye onto activated carbon indicate that bench scale studies could provide realistic estimates of sorption rate and capacity in large scale columns. The model assumes that a packed column consists of a consecutive series of finite increments of packing which are in contact with a liquid phase that is maintained at an essentially constant dye concentration during its residence time in that increment. The liquid phase is assumed to move through the column in plug flow. Small scale studies provide the necessary correlations between sorbate concentration and maximum sorption capacity, and between sorbate removal rates and unfilled capacity which could then be applied to larger scale sorption systems.

Greez and Sing (19) concluded that for a given gas and a unit weight of a given adsorbent, the amount of gas adsorbed at equilibrium is a function of the final pressure and temperature

$$m = F(p, T), \text{ gas, solid} \quad (2.2)$$

The plot of the amount adsorbed m , against the pressure at constant temperature is called adsorption isotherm;

$$m = F(p)_{\text{gas, solid, T}} \quad (2.3)$$

Putting concentration at equilibrium, C^* instead of pressure, p , (2.2) and (2.3) can be used for liquid solid system.

Dendrick and Beckmann (19) pointed out that capacity on isothermal adsorption is not effected by the adsorbent size. In the experiment, he studied adsorption of 2-4-dichlorophenoxyacetic acid from dilute aqueous solution on granular activated carbon. The adsorbed isotherm was measured over the range of liquid concentration from 0.2 to 95% of saturation, and no effect was noted on the capacity when the granular adsorbent was crushed to a fine powder as shown in Fig. 2.1. And Miller and Clump (20) concluded from the experiment of adsorption of phenol by activated carbon that the carbon dosage effects the capacity of adsorption. The results of the experiment were plotted in Fig. 2.2 The majority of tens of thousands of adsorption isotherms for gases grouped into five types. The classification originally proposed by Brunauer, Deming, Deming and Teller (BDDT)(21), nowadays is commonly defined as the Brunauer, Emmett and Teller (BET)(22) classification. These types are shown in Fig. 2.3. For adsorption in liquid phase, Giles et al have also classified isotherms to four main types, with subdivisions of each type, shown in Fig. 2.4. The main types are

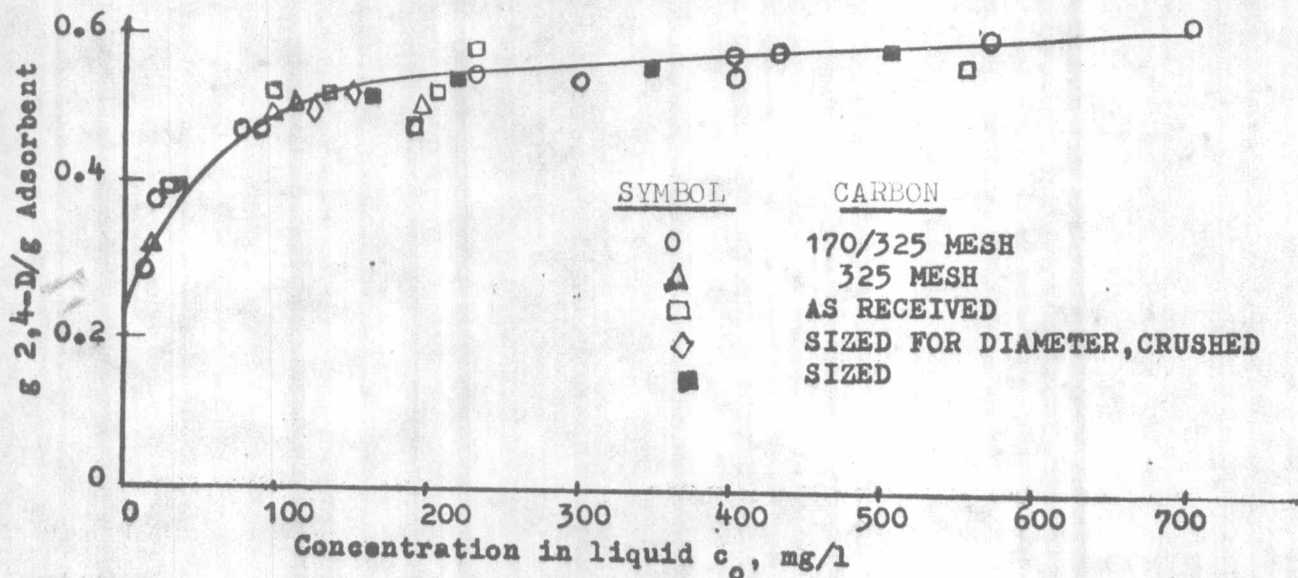


Fig.2.1 Effect of adsorbent preparation on adsorption isotherm of 2,4-Dichlorophenoxyacetic acid

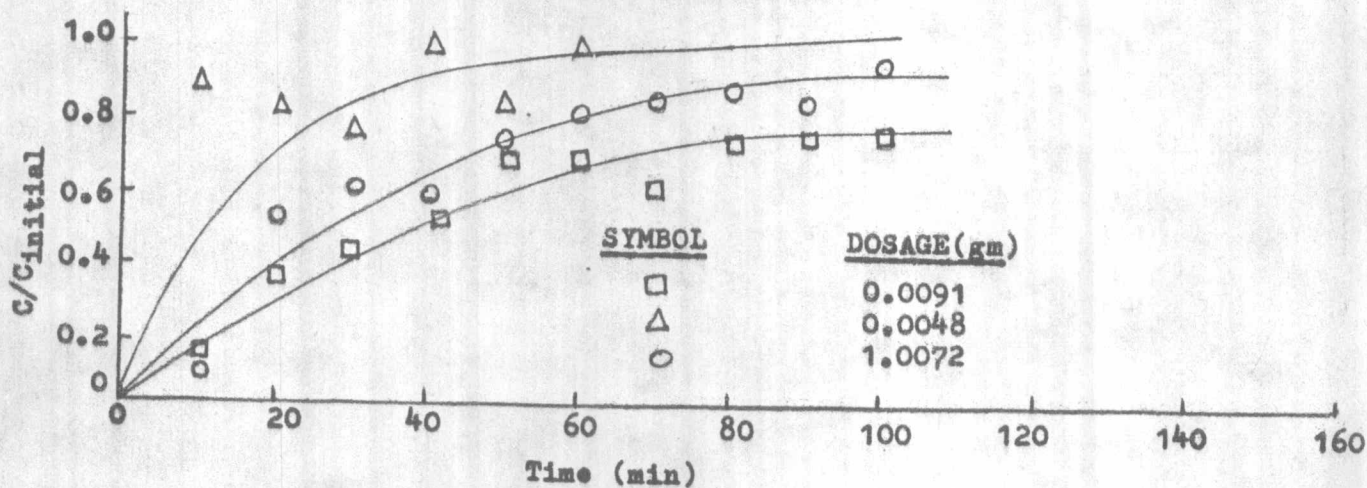


Fig.2.2 The effect of carbon dosage on uptake of phenol from 1 liter of solution at high agitation, 1,000 rev./min.

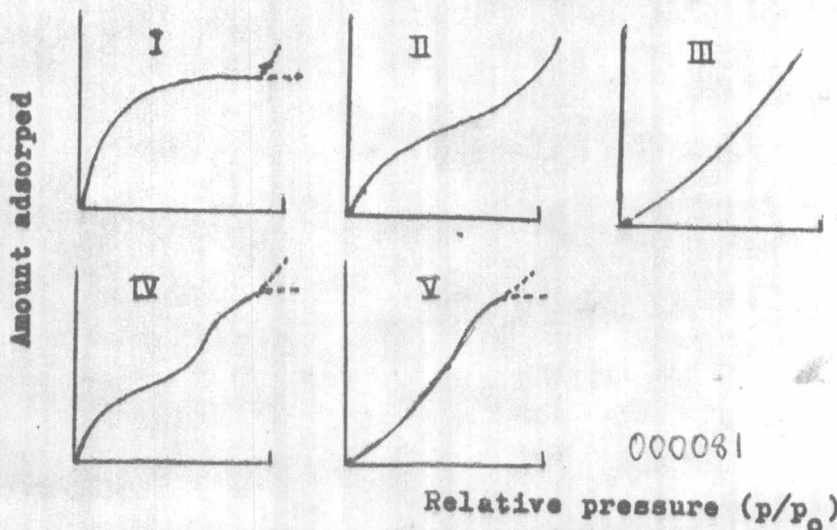


Fig.2.3 The five types of adsorption isotherm in the classification of BET.

characterized by the curvature of the isotherm near the origin.

The classifications of isotherms for both gas phase and liquid phase is found not cover all of the isotherms. For such example, found by Amberg et al (23) for the adsorption of krypton on activated carbon as shown in Fig.2.5

After some time an adsorption equilibrium is reached when the number of molecules leaving the surface of the adsorbent is equal to the number of molecules being adsorbed on the surface. Tabbutt (17) et al stated that it is convenient to describe the nature of an adsorption reaction by relating the adsorption capacity to the concentration of solute remaining in solution at equilibrium, such a relation being term an adsorption. A number of adsorption theories have been developed as mathematical models of the process such as Langmuir, BET and Freundlich.

Langmuir (24) theory proposed from the assumption that the adsorbed layer can be only one molecule thick. Langmuir proposed a relation between concentration in the solution and the adsorbed quantity on the assumption that equilibrium is established between the rate of adsorption and the rate of desorption. In this case, the equation is

$$m = \frac{abC}{1 + aC} \quad (2.4)$$

where m = mass adsorbate adsorbed/mass of adsorbent

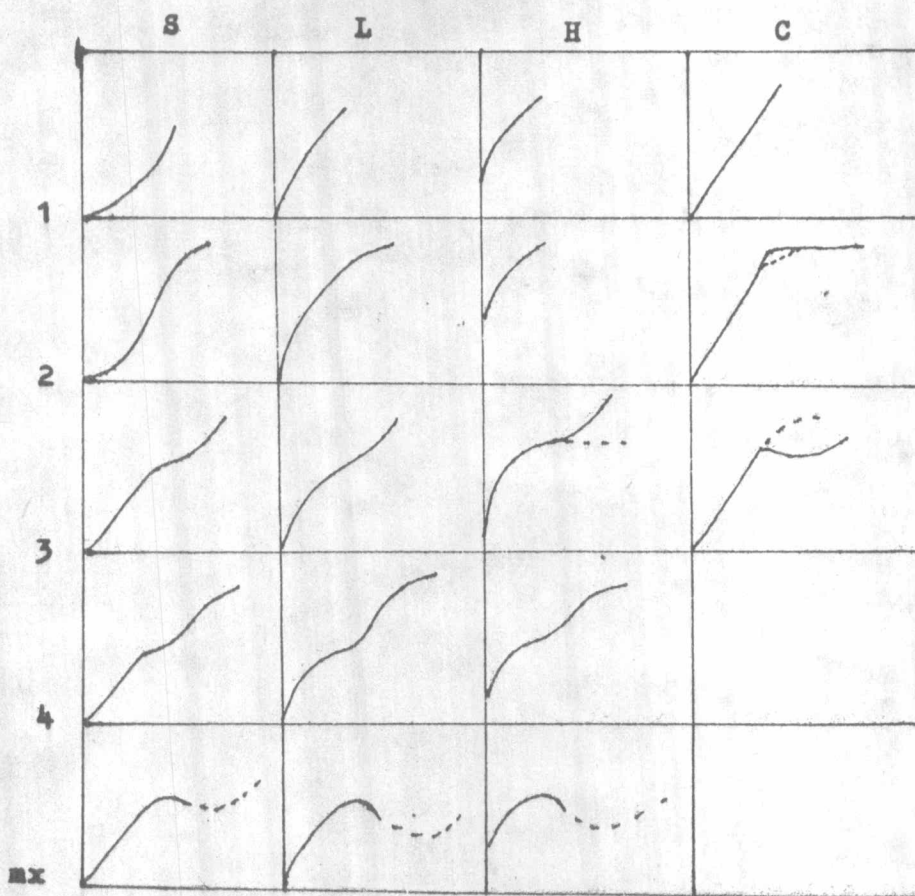


Fig.2.4 The four types of adsorption isotherm for liquid phase

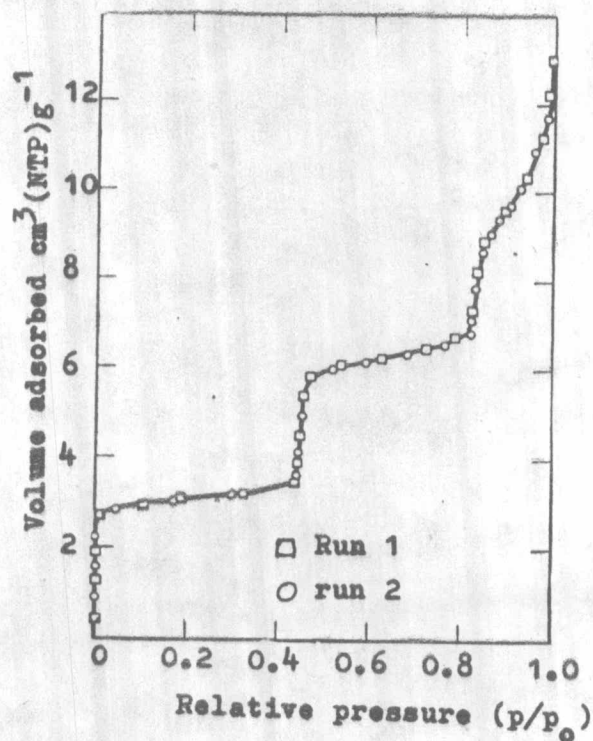


Fig.2.5 An adsorption isotherm which does not fit into the BET classification. This is an isotherm for the adsorption of krypton at -183° on a carbon graphitized at 2700°C .

$a, b = \text{constant}$

$C = \text{Bulk concentration of liquid phase}$

BET (22) isotherm proposed from a theory of multi-molecular adsorption. The assumption in this case is that the same forces which are effective in condensation are also largely productive of the binding energy of multi-molecular adsorption.

$$\frac{m}{m_m} = \frac{\bar{d} \cdot C/C_S}{1 + d C/C_S} \quad (2.5)$$

where $m_m =$ mass adsorbate per unit mass of adsorbent for monomolecular adsorption.

$d = \text{constant}$

$C_S =$ saturated concentration of liquid phase.

Freundlich (25) equation, relates the amount of impurity in solution phase to that in the adsorbed phase,

$$m = A c^{1/n} \quad (2.6)$$

Weber (26) described that examination of the isotherm data of glucose, sucrose, m-cresol adsorptions showed that the Freundlich equation with appropriate values of n was able to provide a reasonable fit in most cases. The Langmuir expression rarely provided a satisfactory model for the experimental results.

2.2.2 Adsorption in Liquid Phase

According to Weber and Keinath (27), adsorption on active carbon has for some time been recognized in the chemical industries as an effective unit operation for a wide range of solute-solvent separation. They also described that direct extrapolation of operating conditions for adsorption from relatively straight forward process applications to waste water treatment applications was not feasible. Adsorption on active carbon for waste treatment is found complicated by the heterogeneity of the solute system, such as concentration and composition of the waste components, the presence of particulate matter and dissolved gases, the variability and relative control of systemic variables as pH. Weber and Keinath (27) pointed out that dictating the method and specific conditions of operation, certain qualitative operating criteria can be set forth on the basis of knowledge of the general behavior of adsorption systems. They studied adsorption of sulfonated alkylbenzene on Columbia LC carbon by varying feed rate, particle size, solute concentration, pH and related to adsorptive capacity.

Adsorptive capacity data for adsorption liquid phase at different effective variables increases with contact time as shown in Fig.2.6 for the adsorption of fluorescent dye on activated carbon studied by Peterson et al (18).

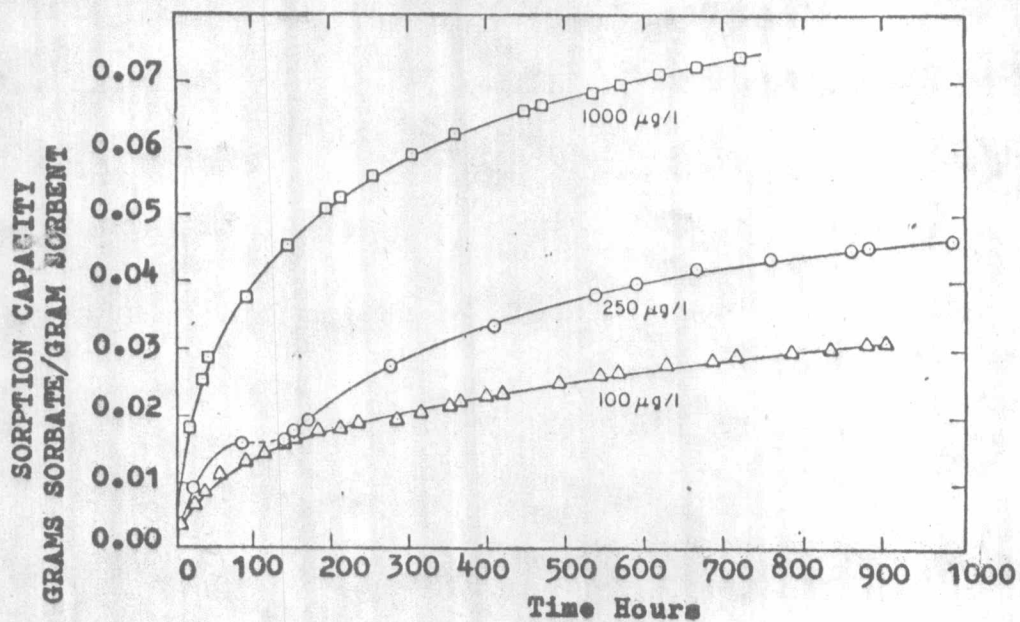


Fig. 2.6 Constant concentration uptake of dye

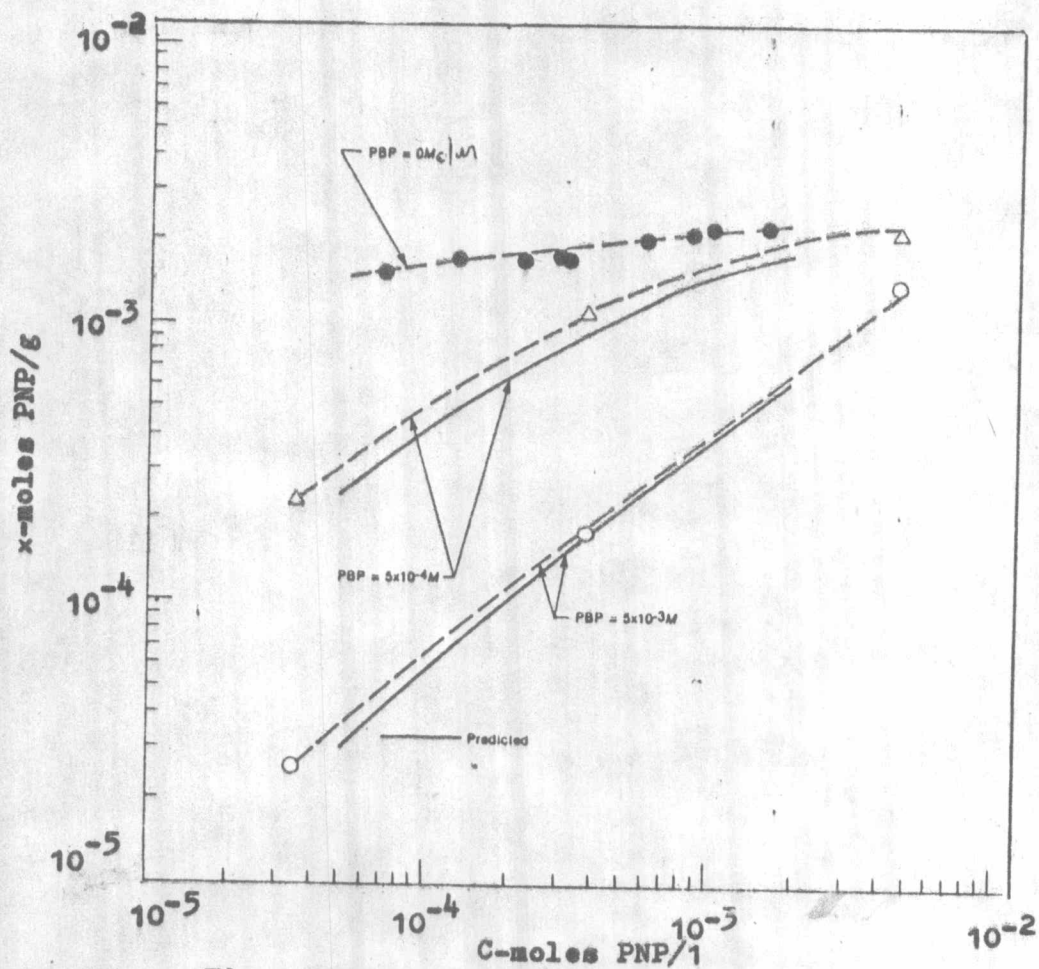


Fig. 2.7 Isotherms for p-Nitrophenol Adsorption from a solution containing neutral p-Nitrophenol and neutral p-Bromophenol; 33

Chow and David (28) stated that the most important parameters for adsorption was emphasized on contact time, comparison to those bed lengths and flow rates. And they also emphasized that carbon dosage was specified for each size of the bed.

The adsorption of traces of tetra- and pentavalent vanadium from pure aqueous solutions and concentrated solutions of NaCl by activated charcoals was studied by Kostyuchenko et al (29). All the variables such as method of preparation, the nature of surface and texture of the charcoals, the concentration of components in the mixture, the pH of medium, etc. were studied. They were able to understand the actual mechanism of the adsorption of vanadium and to give reliable criteria for selecting sorbents for recovering of vanadium from industrial solutions for the production of Cl_2 .

Many studies of carbon adsorption from single solute systems have been conducted, but natural waters contain a mixture of organic substances. Some information can be obtained from simplified systems, such as bisolute systems.

Jain and Snoeyink (30) studied competitive adsorption of bisolute mixture of organic anions and neutral species. Typical results are shown in Fig. 2.7.

As can be seen in this figure, the presence of 5×10^{-3} Molar p-promophenol reduced the capacity of p-nitrophenol by nearly two orders of magnitude at an equilibrium concentration of 5×10^{-5} Molar. The Langmuir competitive model, which assumes competition among species for various sites, could describe accurately the adsorption from a solution of these compounds in the neutral form. And a modification of the Langmuir equation to account for some adsorption without competition was moderately successful. They also pointed out that much adsorption without competition is expected if there is wide variation in molecular size of adsorbate because of the pore size distributions of the carbons.

From data concerning the adsorption of five binary mixtures of organic substances with different thermodynamic characteristics on activated KAD coal from aqueous solutions, Kiricheko et al (31) pointed out that the decrease in the adsorption of the components of a mixture is not directly dependent on their relative displacement.

Herzing et al (32) studied the adsorption of two compounds that cause earthy-musty odor in water, 2-methylisoborneol and geosmin, in the presence of commercial humic acid and organic matter found in well water. Significant reductions in capacity owing to the presence of these materials were observed with the magnitude of reduction

being dependent on the type of organic matter, both the odor compound and the natural organic matter, and the relative concentrations present. pH was not of significance for these adsorbates.

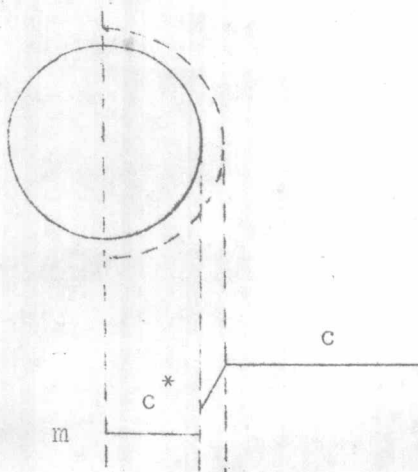
2.2.3 Kinetic Adsorption

Ganho (33) state that two significant steps in adsorption of solid in liquid phase used for explaining mechanism of adsorption are external and internal diffusion.

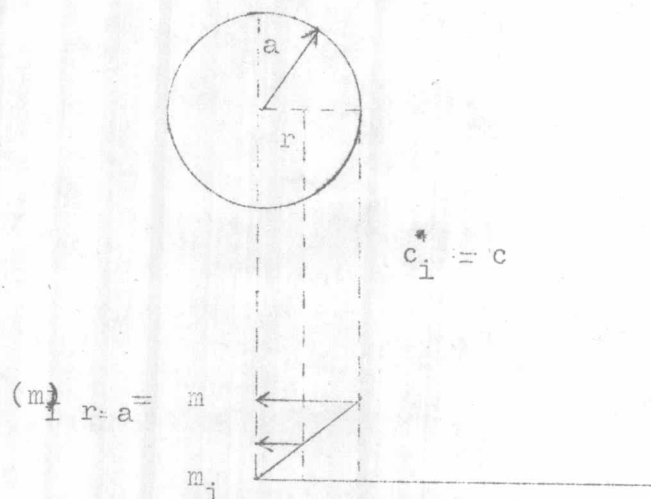
External diffusion is the transfer of solute from bulk solution to the surface or macropores of adsorbent. It's rate can be described by this below equation;

$$\frac{dm}{dt} = k_f S (C - C^*) \quad (2.7)$$

where C = bulk concentration of liquid phase
 C^* = concentration of liquid at solid interface
 k_f = external mass transfer coefficient
 m = mass of solute adsorbed/mass of adsorbent
 at any time



Internal diffusion is the transfer of solute from surface of adsorbent into the pores.



The equation involves mass transfer rate for internal diffusion is;

$$\frac{dm}{dt} = k_p (a_v)_c (m^* - m) \quad (2.8)$$

where k_p = internal mass transfer coefficient
 $(a_v)_c$ = specific volume (surface area of adsorbent per unit volume of bed)
 m^* = gm adsorbate/gm adsorbent equilibrium with concentration C^*
 m = mass of solute adsorbed/mass of adsorbent at any time.

2.3 Fluidization

2.3.1 Definition

According to Kunii (35), fluidization is operation by which fine solids are transformed into a fluid-like state through contact with a gas or liquid.

2.3.2 Phenomenon of Fluidization

Kunii (34) described that passing of fluid upward through a bed of fine particles at low flowrate, fluid merely percolates through the void spaces between stationary particles. This is a fixed bed. With an increase flow rate, the expanded bed is formed. At this condition, particles move apart and a few are seen to vibrate and move about restricted region. A point of higher velocity at which the particles are all just suspended in the upward flowing gas or liquid. The pressure drop through any section of the bed about equals the weight of liquid and particles in that section. The bed is considered to be just fluidized and is referred to as an incipiently fluidized bed or a bed at minimum fluidization. As increasing flow rate above minimum fluidization usually results a particulate fluidized bed.

Davidson et al (35) stated that particulate fluidization generally occurs in liquid-solid system, is a phenomena

that the bed will continue to expand as the flow rate increases so that the average distance between the particles will become greater, large scale bubbling or heterogeneity is not observed. Aggregative fluidization is usually form in gas-solid system, the excess fluid will pass through the bed in the form of bubbles, giving rise essentially to a two-phase system. With an increase in flow rate beyond minimum fluidization, large instabilities with bubbling and channeling of gas are observed. At higher flow rate agitation becomes violent and the movement of solids becomes more vigorous.

Vilhelm and Kwauk (36) have suggested using the Froud number as a criterion for the type of fluidization obtained. In generally aggregative fluidization is obtained at Froude Group values above unity, and particulate fluidization at values below unity.

Kunni(34) pointed out that both gas and liquid fluidized bed are considered to be dense-phase fluidized bed as long as there is a fairly clearly defined upper limit or surface to the bed. At the condition of higher flow rate at which the upper surface of the bed disappears the solids are carried out of the bed with fluid stream is called dispersed, dilute-or lean-phase fluidized bed.

A kind of fluidized bed shown in Fig.2.8, slugging is a specially serious phenomenon strongly affected by the long,

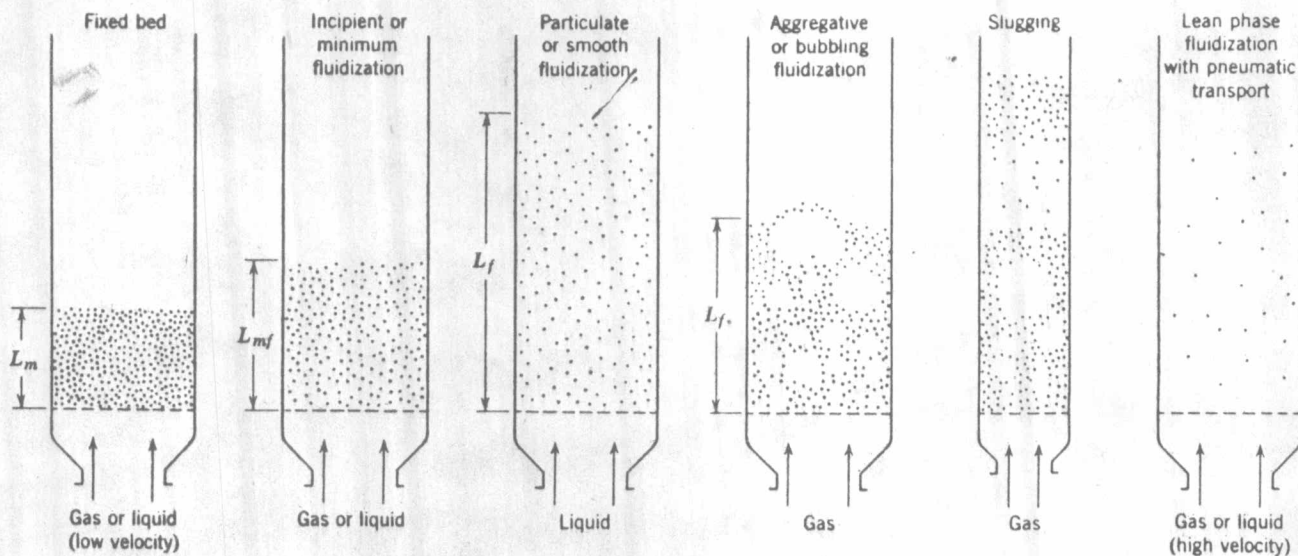


Fig.2.8 Various kinds of contacting of a batch of solids by fluid

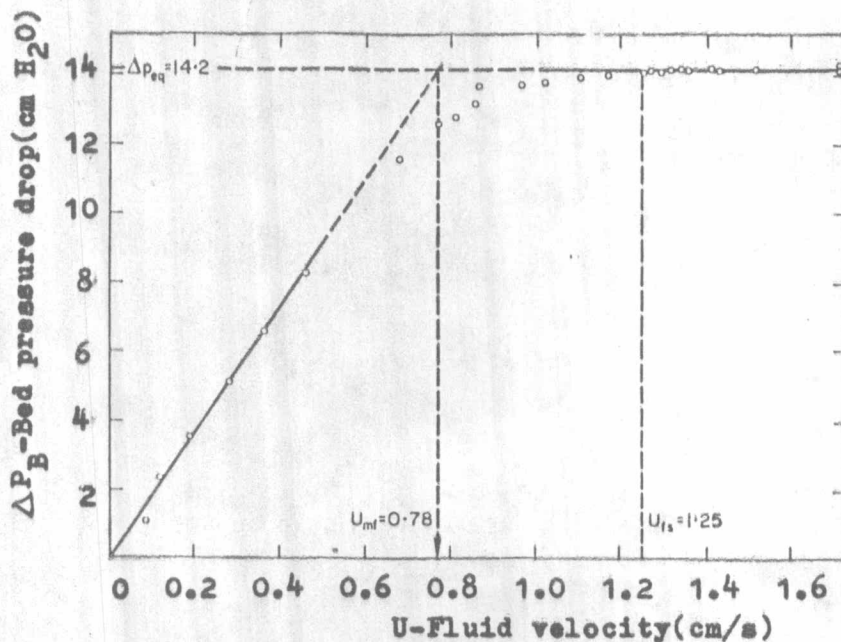


Fig.2.9 Experimental determination of minimum fluidizing velocity U_{mf} , and minimum velocity for full support U_{f8} . Diakon (perspex) powder (surface mean diameter 126 microns)-atmospheric pressure. Bed weight 1240 g; height - 23 cm; diameter 10 cm.

narrow fluidized bed. In this fluidized bed, gas bubbles grow as they rise, and in deep enough bed they may become large enough to spread across the vessel. Thereafter the portion of the bed above the bubbles is pushed upward, as by a piston. Particles rain down from the slug and it finally disintegrates. At about this time another slug forms and this unstable oscillatory motion is repeated.

2.3.3 Pressure Drop

According to Richardson (37), the relationship between pressure drop and velocity will be that. Which is applicable to a fixed bed, for fine particles, the Carman-Kozeny equation will hold with a linear relationship as;

$$\Delta P = \frac{5(1-\epsilon)^2 uL \mu (a_v)^2}{\epsilon^3} \quad (2.9)$$

When the velocity has reached such a value that the frictional pressure drop is equal to the buoyant weight per unit area of the particles (ΔP_{eq}) any further increase in velocity must result in a slight upward movement of the particles forming the bed. The resistance of particles to fluid flow is decreased, the voidage of bed will increase and the pressure drop will remain constant (ΔP_{eq}). The pressure drop over the fluidized bed will be given by

$$\Delta P = (p_s - p_f)(1-\epsilon) L.g \quad (2.10)$$

where L represents bed height and ϵ represents voidage.

Mantell (2) pointed out that pressure drop was effected by different linear velocities of fluid, different bed densities and different sizes of activated carbon.

2.3.4 Minimum Fluidizing Velocity

2.3.4.1 Definition

Richardson (37) explained that as the minimum fluidizing velocity has no absolute significance, it is desirable to standardize a method of determination so that the characteristics of different systems can be compared. This is most conveniently done by using the graph of frictional pressure drop against velocity. The velocity at the intersectional point of fixed bed region line and fluidized bed region line is minimum fluidizing velocity. The whole of the bed is not fluidized until the particles are fully supported in the fluid and the pressure drop becomes exactly equal to the buoyant weight per unit area, ΔP_{eq} . The minimum velocity at which this occurs will be called. "The full supporting velocity", u_{fs} . For the experimental results shown in Fig. 2.9 u_{fs} is more than 50% greater than u_{mf} .

2.3.4.2 Calculation of minimum fluidizing velocity

Richardson (37) also explained that elimination the problems of carrying out on experimental determination

it is useful to be able to calculate approximately the value of the minimum fluidizing velocity. This may be done by using an expression for the relation between pressure drop and superficial velocity for a fixed bed and putting a pressure drop equals to the bouyant weight of the particles. This does, of course, necessitate a knowledge of voidage of the bed at minimum fluidizing velocity (u_{mf}). This will depend on the shape and size range of the particles, but a value of about 0.4 would be appropriate for approximately spherical particles.

If the bed expands, the product $(1-\epsilon)L$ will remain constant. Using the values of each term in Eq.(2.10) appropriate to the condition of incipient fluidization.

$$\Delta P = (\rho_s - \rho_f)(1 - \epsilon_{mf})L_{mf}g \quad (2.11)$$

relates this equation to those of Carman-Kozeny

$$\Delta P = \frac{5(1 - \epsilon_{mf}^2)L_{mf} \cdot U_{mf} \cdot \mu (a_v)_p^2}{(\epsilon_{mf})^3} \quad (2.12)$$

results

$$U_{mf} = \frac{\epsilon_{mf}^3 (\rho_s - \rho_f) g}{5(1 - \epsilon_{mf}^2)(a_v)_p^2 \mu} \quad (2.13)$$

For uniform spherical particles $(a_v)_p = 6/d$ and

taking $\epsilon_{mf} = 0.4$

$$U_{mf} = \frac{0.00059 d_p^2 (\rho_s - \rho_f) g}{\mu} \quad (2.14)$$

For larger particles, a more general equation such as the Blake, Carman, or Ergun equation must be used for the pressure drop through fixed bed. Using Ergun⁽³⁸⁾ equation;

$$\frac{\Delta P}{L_{mf}} = \frac{150(1-\epsilon_{mf})^2 \mu U_{mf}}{\epsilon_{mf}^3 d_p^2} + \frac{1.75(1-\epsilon_{mf}) \rho_f U_{mf}^2}{\epsilon_{mf}^3 d_p} \quad (2.15)$$

The pressure drop in Eq.(2.15) represents two factors, the viscous and the kinetic energy losses. At low Reynolds numbers the viscous losses predominate and Eq.(2.15) simplifies to

$$\frac{\Delta P}{L_{mf}} = \frac{150(1-\epsilon_{mf})^2 \mu U_{mf}}{\epsilon_{mf}^3 d_p^2} \quad \text{Rep} < 20 \quad (2.16a)$$

At high Reynolds numbers, only the kinetic energy losses need be considered; thus Eq.(2.15) simplifies to;

$$\frac{\Delta P}{L_{mf}} = \frac{1.75(1-\epsilon_{mf}) \rho_f u_{mf}^2}{\epsilon_{mf}^3 d_p} \quad \text{Rep} > 1,000 \quad (2.16b)$$

Wen and Yu⁽³⁹⁾ have suggested two expressions for evaluating the value of unknown ϵ_{mf} and ϕ_s as

$$\frac{1}{\phi \epsilon_{mf}^3} \approx 14 \quad \text{and} \quad \frac{1-\epsilon_{mf}}{\phi_s^2 \epsilon_{mf}^3} \approx 11$$

By replacing in Eq.(2.16a) results for small particles

$$u_{mf} = \frac{d_p^2 (\rho_s - \rho_f) g}{1650 \mu} \quad \text{Rep} < 20$$

and for large particles $u_{mf}^2 = \frac{d_p(\rho_s - \rho_f)g}{24.5\rho_f g}$ Rep > 1,000

Many alternate procedures have been proposed for calculating u_{mf} such as by Leva⁽⁴⁰⁾

$$\frac{\Delta P}{L_{mf}} = \frac{2f_m G_{mf}^2 (1 - \epsilon_{mf})^{3-\bar{n}}}{d_p g \rho_f \phi_s^{3-\bar{n}} \epsilon_{mf}^3} \quad (2.17)$$

where \bar{n} = exponent, a function of the modified Reynolds number Rep, dimensionless

G = fluid superficial mass velocity base on empty chamber cross section, gm/sec.cm²

f_m = friction factor, a function of Rep

The value ϵ_{mf} can be evaluated from

$$\epsilon_{mf} = 1 - \frac{m_c}{L_{mf} S \rho_s} \quad (2.18)$$

where m_c = weight of solid in bed

S = cross-sectional area of bed

2.3.5 Adsorption in Fluidized Column

For fine adsorbent particle size can lead to serious problems of clogging in packed beds operation, it has been found that avoiding those problem can be associated with fluidized-solid contacting technique. Weber et al⁽²⁷⁾ studied

about rate of adsorption of sulfonated alkylbenzene from aqueous solution by activated carbon in fluidized column. Mass transfer rates were evaluated for various feed rates and various particle size. Mass transfer coefficient were evaluated and related to those Reynolds number and surface area of adsorbent. Ganho et al⁽³³⁾ also studied adsorption in fluidized column. Phenol adsorption from dilute aqueous solutions was studied using fluidized bed of active carbon, for different particles sizes and feed rate, the external and internal diffusion were evaluated.

Adsorption in fluidized column of acetic acid was also studied by Sagetong,⁽⁴¹⁾ Concentrations of solute, sizes of adsorbent and feed rates were varied for the total 11 experiments. Mass transfer rates were evaluated for all experiment and were related in graphical results with those variables; concentration of solute, size of adsorbent and feed rate. Mass transfer coefficients were also calculated and relates to two variables; Reynolds number and surface area.