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Isotherm Adsorption of Solutes

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ABSTRACT

Adsorption is the accumulation of molecules on a solid surface due to unsaturated surface forces. In solutions, adsorption is influenced by factors such as the type of adsorbent and adsorbate, surface area, solute concentration, and temperature. The relationship between the amount adsorbed per unit area or mass of adsorbent and solute concentration at constant temperature is described by adsorption isotherms. An adsorbent is the material that captures substances, while an adsorbate is the substance retained. Adsorbents can be polar or nonpolar; polar adsorbents are further classified as acidic (e.g., silica, chlorosil) or basic (e.g., amines, magnesia). Basic adsorbents have a higher affinity for acidic compounds such as phenols and carboxylic acids. Adsorbents are porous, allowing gases or solutes to be bound on their surfaces. This distinguishes adsorption, which forms a surface layer, from absorption, where a fluid is taken up into another fluid. In this study, activated carbon was used as an adsorbent, and the obtained log C values were 0.28, 0.91, 1.26, 0.90, 2.15, and 3.39. The results indicate that increasing adsorption time decreases the required titrant volume. The calculated slope (0.9032) shows effective adsorption behavior.

Keywords: Adsorption; adsorbate; adsorbent.

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1. Introduction

Adsorption is the phenomenon of the accumulation of molecules of a substance on the surface of another substance as a result of the unsaturation of surface forces. For adsorption in solutions, the amount of adsorbed substance depends on several factors: the type of adsorbent, the type of adsorbate (the substance being adsorbed), the surface area of the adsorbent, the concentration of the solute, and the temperature. For a given adsorption system, the relationship between the amount of substance

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adsorbed per unit area or per unit weight of adsorbent and the solute concentration at a certain temperature is called an adsorption isotherm [3].

Adsorption is a phenomenon involving physical, chemical, and electrostatic interactions between the adsorbate and the adsorbent on the adsorbent surface. The attractive forces of a solid are classified into two types: physical forces and chemical forces, each resulting in physical adsorption and chemical adsorption, respectively. Adsorption is a surface phenomenon in which there is an increase in the concentration of certain components at the interface between two phases. Adsorption can be categorized into two types: physisorption (physical adsorption) and chemisorption (chemical adsorption) [8].

An adsorbent is a substance that adsorbs another substance, while an adsorbate is the substance being adsorbed. Adsorbents can be classified into polar and non-polar types. Polar adsorbents can further be divided into acidic and basic adsorbents. Acidic adsorbents include silica and chlorosil, while basic adsorbents include amines and magnesia (unless acid-treated). Basic adsorbents are more effective at retaining acids, for example, phenol derivatives, cresols, tropol, and carboxylic acids [4].

2. Materials and Method

The solid–liquid interface plays a fundamental role in various industrial and scientific processes, particularly in catalytic reactions, electrochemical systems, and nanomaterial applications in aqueous environments. The interaction between solute species and the solid surface is referred to as adsorption at the solid–liquid interface. For instance, NO_2^- ions can be adsorbed onto the surface of a Cu–Pd alloy in aqueous solution (Figure 1). In this context, the solid phase is designated as the adsorbent, while the solute species undergoing adsorption are referred to as the adsorbate.

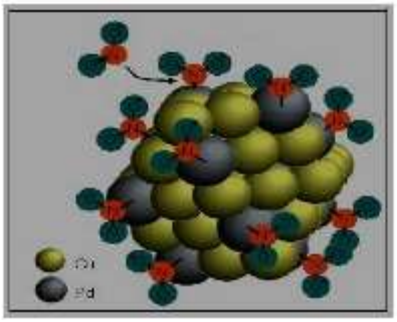

Figure 1. Examples of Absorbates

If a liquid or gas penetrates into the inner particles of a solid, it is called absorption, for example, water vapor on activated carbon (Figure 2).

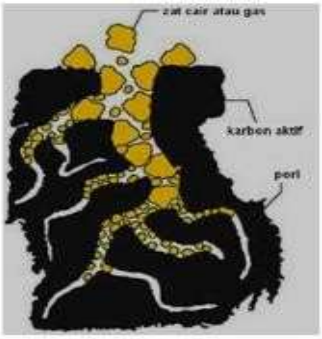

Figure 2. Absorption of liquid or gas in activated carbon

A solid's surface is typically rough, which makes figuring out its true surface area challenging. It is therefore expressed in mass units for adsorbents and in volume units (ml) of gas at STP (0ºC and 1 atm) for adsorbate gas. This implies that:

$$\text{Adsorption Unit} = \frac{vol\ of\ adsorbate\ gas}{mass\ of\ adsorbent}$$

$$= \frac{mL}{gram}$$

At certain temperature (T) and pressure (P), the volume (V) of gas adsorbed is directly proportional to the number of moles of gas per gram of adsorbent. Adsorption at constant temperature is called isothermal adsorption [1]. Adsorption is the ability of a solid material to capture a component in a gas or liquid mixture onto its surface. This process occurs due to the tendency of molecules on the solid surface to attract other molecules in the gas or liquid mixture as a result of the forces acting on them [11].

An adsorption isotherm represents the equilibrium relationship between the chemical potential of the adsorbate in the gas or liquid phase and its chemical potential on the surface of the adsorbent at constant temperature. Equilibrium is reached when the adsorption rate equals the desorption rate. There are three main types of adsorption isotherms: Langmuir, Freundlich, and BET isotherms [10].

Adsorption is a method used to remove pollutants from wastewater because it involves the adsorption of ions or molecular substances onto the surface of an adsorbent. There are two types of adsorption: physical and chemical. Adsorption occurs when a fluid is bound to a solid and forms a thin layer on its surface. In contrast, absorption occurs when a fluid is absorbed by another fluid. An "adsorbent" is the solid material that performs adsorption, which is commonly a carbon-based compound. The "adsorbate" is the substance being adsorbed or separated from its solvent [9].

There are several factors that can influence the adsorption process when using a porous solid surface:

a. Surface area of the adsorbent.
   The specific surface area greatly influences the adsorption capacity.
b. The physical and chemical properties of the adsorbate.
   An increase in molecular weight and the number of functional groups, including double bonds and halogens, can enhance the adsorption of a compound.
c. Acidity of the solution
   The adsorption of heavy metal cations (such as Cu(II), Zn(II), Cd(II), Pb(II)) by adsorbents in an acidic medium increases with the rise in pH.
d. Temperature
   A decrease in temperature leads to an increase in adsorption because the adsorption reaction proceeds exothermically.
e. Porosity of the adsorbent.
   The number of pores, pore shape, and pore size determine both the adsorption rate and adsorption capacity.

The surface charge, surface acidity, polarity, and hydrophobicity of the adsorbent are strongly determined by the type of functional groups present on its surface [7].

Tools and Materials

In this experiment, several tools were used, including a burette (50 mL), twelve Erlenmeyer flasks, six funnels, coarse filter paper, pipettes (10 mL, 20 mL), and a 100 mL volumetric flask. The materials used were 0.1 M standard NaOH, oxalic acid solutions (1 M, 0.1 M, and 0.01 M), and activated carbon (approximately 30 grams).

Preparation Process

Prepare six Erlenmeyer flasks. Then, add 5 grams of activated carbon into each flask. To each Erlenmeyer flask, add 100 mL of oxalic acid solution with concentrations of 0.3 M, 0.2 M, 0.1 M, 0.05 M, 0.01 M, and 0.005 M. Shake well and let the mixtures stand for one day (at least six hours). After standing for one day, filter each solution using coarse filter paper. Before performing titration, titrate the oxalic acid solution with NaOH of appropriate concentration using phenolphthalein as an indicator (the endpoint is marked by a color change of phenolphthalein from colorless to pink). Additionally, titrate one of the original oxalic acid solutions with NaOH to determine the exact concentration.

3. Result

Experimental Results

Table 1. Experimental Data Results

$C_2H_2O_4$ approximately	$[C_2H_2O_4]$ actual	[NaOH] standard	Volume $C_2H_2O_4$	Volume NaOH	$[C_2H_2O_4]$ after
0.3	0.3	0.06	3 ml	15.45 ml	0.515
0.2	0.2	0.06	3 ml	3.7 ml	0.123
0.1	0.1	0.06	6 ml	3.3 ml	0.055
0.05	0.05	0.06	12 ml	15 ml	0.125
0.01	0.01	0.06	6 ml	4.9 ml	0.007
0.005	0.005	0.001	6 ml	2.4 ml	0.0004

Table 2. Determination of the Freundlich Isotherm Equation

X	C	Log x	Log c	1/x	1/C
1.545	0.515	-0.189	0.28	0.64	1.94
0.369	0.123	0.43	0.91	2.71	8.13
0.33	0.055	0.48	1.26	3.03	18.18
1.5	0.125	-0.17	0.90	0.66	8
0.042	0.007	1.37	2.15	23.80	142.8
0.0024	0.0004	2.62	3.39	416.67	2,500

Table 3. Linear Regression

y	x	yx	X^2
0.189	-0.28	-0.053	0.035
-0.43	-0.91	0.391	0.184
-0.48	-1.26	0.604	0.230
0.17	-0.90	-0.153	0.029
-1.37	-2.15	2.0945	1.877

2.62	-3.39	-8.88	6.864
0.359	-8.89	-5.146	9.219

Perhitungan

1. Standardization of NaOH

   M1.V1 = M2.V2

   M1.2210ml = 0.3M.5ml

   M 1 = 0.06M

2. NaOH 0.01M

   $$M1 = \frac{M2.V2}{V1} = \frac{0.01M.5mL}{17.5mL} = 0.002\ \text{M}$$

3. NaOH 0.001M

   $$M1 = \frac{M2.V2}{V1} = \frac{0.05M.5mL}{15mL} = 0.001\ \text{M}$$

4. Calculation of $H_2C_2O_4$ after mixing with activated charcoal
   1) M1.V1 = M2.V2

      $$M2 = \frac{M1.V1}{V2} = \frac{0.1M.15.45mL}{3mL} = 0.515\ \text{M}$$

   2) M1.V1 = M2.V2

      $$M2 = \frac{M1.V1}{V2} = \frac{0.1M.3.7mL}{3mL} = 0.123\ \text{M}$$

   3) M1.V1 = M2.V2

      $$M2 = \frac{M1.V1}{V2} = \frac{0.1M.3.3mL}{6mL} = 0.055\ \text{M}$$

   4) M1.V1 = M2.V2

      $$M2 = \frac{M1.V1}{V2} = \frac{0.1M.15mL}{12mL} = 0.125\ \text{M}$$

5) M1.V1 = M2.V2

$$M2 = \frac{M1.V1}{V2}$$

$$= \frac{0.01M.4.7mL}{6mL}$$

$$= 0.007 \text{ M}$$

6) M1.V1 = M2.V2

$$M2 = \frac{M1.V1}{V2}$$

$$= \frac{0.001M.2.4mL}{6mL}$$

$$= 0.0004 \text{ M}$$

5. Calculation of X

1) M . V
   = 0.515M.3ml
   = 1.545
2) M . V
   = 0.123M.3ml
   = 0.369
3) M . V
   = 0.055M.6ml
   = 0.33
4) M . V
   = 0.125M.12ml
   = 1.5
5) M . V
   = 0.007M.6ml
   = 0.042
6) M . V
   = 0.0004M.6ml
   = 0.0024

$$\text{Slope} = \frac{\Delta y}{\Delta x}$$

$$= \frac{0.189-(-2.62)}{-0.28-(-3.39)}$$

$$= \frac{2.809}{3.11}$$

$$= 0.9032\text{M}$$

$$\alpha = \frac{\sum y \sum x - n \sum yx}{\sum x \sum x - n \sum x^2}$$

$$= -0.2060$$

$$bc = \frac{\sum yx \sum x - \sum y \sum x^2}{\sum x \sum x - n \sum x^2}$$

$$= -55.8509$$

Graph between -log x and -logC

Linear Regression

$$\text{Slope} = \frac{\Delta y}{\Delta x}$$

$$= \frac{ymax - ymin}{Xmax - Xmin}$$

$$= \frac{2.62-(-1.37)}{-0.28-(-3.39)}$$

$$= \frac{3.99}{3.11}$$

$$= 1.2829$$

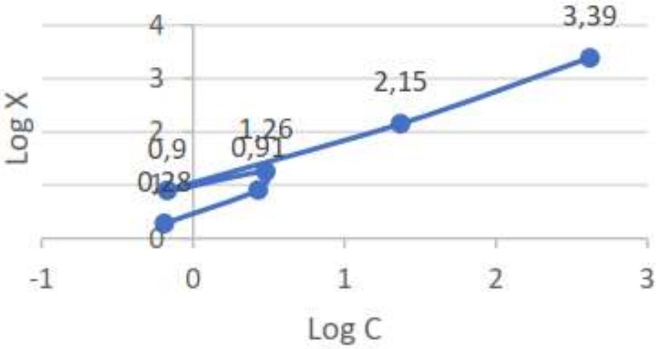

Figure 3. Linear Regression Equation

4. Discussion

In this experiment on the adsorption isotherm of solutes, adsorption proceeds through several sequential stages. Initially, the contaminant molecules diffuse from the solution onto the outer surface of the activated carbon particles. Subsequently, these molecules migrate into the pores of the adsorbent, and finally, adsorption occurs on the internal pore surfaces where the interaction between the adsorbate and adsorbent becomes dominant. Activated carbon serves as the adsorbent because it is a porous material with a very large internal surface area and a particle diameter generally ranging from 0.5 to 200 μm [6]. The extensive pore structure and high surface area of activated carbon play a crucial role in enhancing adsorption capacity and kinetics.

To prevent contamination from ambient air, the mixture of oxalic acid and activated carbon was covered with aluminum foil. Shaking was carried out to achieve a homogeneous mixture and to accelerate the adsorption process, since increased collisions between adsorbate and adsorbent particles promote faster adsorption. The subsequent resting period allowed Van der Waals forces to act optimally between the adsorbate molecules and the adsorbent surface. During continuous shaking, adsorption is less efficient because constant particle motion inhibits the entry of adsorbate molecules into the adsorbent pores. Therefore, a resting phase is essential for effective adsorption to take place [3].

This experiment validates Freundlich's adsorption isotherm theory, which describes adsorption on heterogeneous surfaces. The adsorption of oxalate onto activated carbon involves the interaction of oxalate molecules with the wide and deep pores of the carbon, leading to multilayer adsorption. The mechanism is mainly governed by Van der Waals forces and weak chemical interactions between the oxalate molecules and the carbon surface. These interactions result in the formation of an adsorbed layer that reduces the oxalate concentration in the solution.

The relatively high adsorption capacity observed can be attributed to several factors. First, the large surface area and pore volume of activated carbon enable it to retain a substantial number of oxalate molecules. Second, operational conditions such as contact time, temperature, and the initial concentration of oxalate significantly influence the adsorption efficiency. Minor deviations in the titration endpoint determination may also contribute to experimental variation.

The surface area of activated carbon is a key factor that determines adsorption performance. During the production of activated carbon, the activation process—which involves thermal treatment—is essential for developing the pore network, enlarging pore size, and increasing surface area, all of which enhance adsorption capability [5].

In general, the adsorption process is affected by several parameters, including:

1. Surface area of the adsorbent.
2. Particle size of the adsorbent.
3. Contact time.

4. Solubility of the adsorbent.
5. Affinity of the solute for the adsorbent.
6. Molecular size in relation to pore size.
7. Temperature.
8. Degree of ionization of the adsorbate molecules [2].

Based on the experimental data, the calculated log C values were 0.28, 0.91, 1.26, 0.90, 2.15, and 3.39. The results show that as adsorption time increases, the titrant volume required decreases, indicating that more oxalic acid molecules are adsorbed onto the activated carbon surface. From the plot of log x versus log C, the slope value obtained was 0.9032, confirming that the adsorption follows the Freundlich isotherm model. This value suggests multilayer adsorption on a heterogeneous surface, which is consistent with the characteristics of activated carbon as an effective adsorbent for oxalic acid.

5. Conclusions

The experimental investigation of the adsorption isotherm between oxalic acid and activated carbon shows that the process follows the Freundlich adsorption model. This indicates that the adsorption occurs on a heterogeneous surface with multilayer formation. The Freundlich plot yielded a calculated slope value of 0.9032, confirming that the adsorption process was primarily physisorption, driven by intermolecular (van der Waals) forces rather than chemisorption.

A progressive decrease in titrant volume over time indicates enhanced adsorption efficiency. This is because a greater amount of oxalate ions are retained by the activated carbon surface, resulting in a lower equilibrium concentration of oxalate in the solution. The high adsorption capacity of activated carbon is due to its extensive surface area and well-developed pore structure, which promote effective interaction between the adsorbate and adsorbent surfaces.

Furthermore, external operational parameters, including contact time, temperature, and precision in endpoint titration, were found to influence overall adsorption performance and data reliability.

The findings confirm the applicability of the Freundlich isotherm for describing oxalate adsorption on activated carbon and reinforce its potential as an efficient adsorbent for removing oxalate species from aqueous solutions under controlled laboratory conditions.

6. Patents

This study does not result in a patent. The results primarily provide theoretical insights into gas adsorption mechanisms, influencing factors, and adsorption isotherm models (Langmuir, Freundlich, and BET), which serve as a scientific basis for further research in material science and environmental engineering rather than generating intellectual property rights.

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