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Carbon Adsorption for VOCs

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Module 1: Carbon Adsorption for VOCs

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the mechanical and theoretical differences between fixed-bed and canister adsorption systems.
- **Calculate** carbon requirements for continuous and intermittent operations using working capacity and adsorption cycle profiles.
- **Evaluate** capital and annual costs for VOC control systems, including equipment factoring and utility consumption.

Executive Summary: Adsorption is a high-efficiency VOC removal process where gas molecules are physically held by attractive forces on a solid adsorbent, primarily activated carbon. Successful design requires balancing the **working capacity** of the carbon against gas flow rates and regeneration cycles to ensure the system remains below breakthrough limits and lower explosive limits (LEL).

Introduction

In air pollution control, adsorption is employed to remove volatile organic compounds (VOCs) from low to medium concentration gas streams. This process is used when a stringent outlet concentration must be met and/or recovery of the VOC is desired.

- **Physical Adsorption:** A phenomenon where gas molecules passing through a bed of solid particles are selectively held by attractive forces weaker than chemical bonds.
- **Heat of Adsorption:** During adsorption, a gas molecule migrates to the surface of the solid, releasing energy that typically equals or exceeds the heat of condensation.
- **Capacity Factors:** Adsorptive capacity increases with gas phase concentration, molecular weight, diffusivity, polarity, and boiling point.
- **Chemisorption:** This occurs when gases form actual chemical bonds with the adsorbent surface groups.
- **Regeneration:** Most adsorbates can be removed (desorbed) by heating via steam or hot combustion gases, or by reducing pressure (vacuum desorption).

Adsorbents in large-scale use include activated carbon, silica gel, activated alumina, synthetic zeolites, and clays. This section focuses on **activated carbon**.

Types of Adsorbers

Five types of equipment are used in collecting gases: (1) fixed regenerable beds; (2) disposable/rechargeable canisters; (3) traveling bed adsorbers; (4) fluid bed adsorbers; and (5) chromatographic baghouses. Fixed-bed and canister types are the most commonly used.

Fixed-bed Units

Fixed-bed units can be sized for flow rates ranging from several hundred to several hundred thousand cubic feet per minute (cfm).

- **Concentration Range:** VOC concentrations can range from several parts per billion by volume (ppbv) to 25% of the VOC's lower explosive limit (LEL).
- **Intermittent Operation:** The adsorber removes VOC during the source's emission time and begins a desorption cycle after shutdown.
- **Continuous Operation:** A regenerated bed is always available; while one bed is adsorbing, a second is desorbing or idling.
- **Desorption Cycle:** Consists of (1) regeneration by heating (usually steam), (2) bed drying, and (3) cooling to operating temperature.

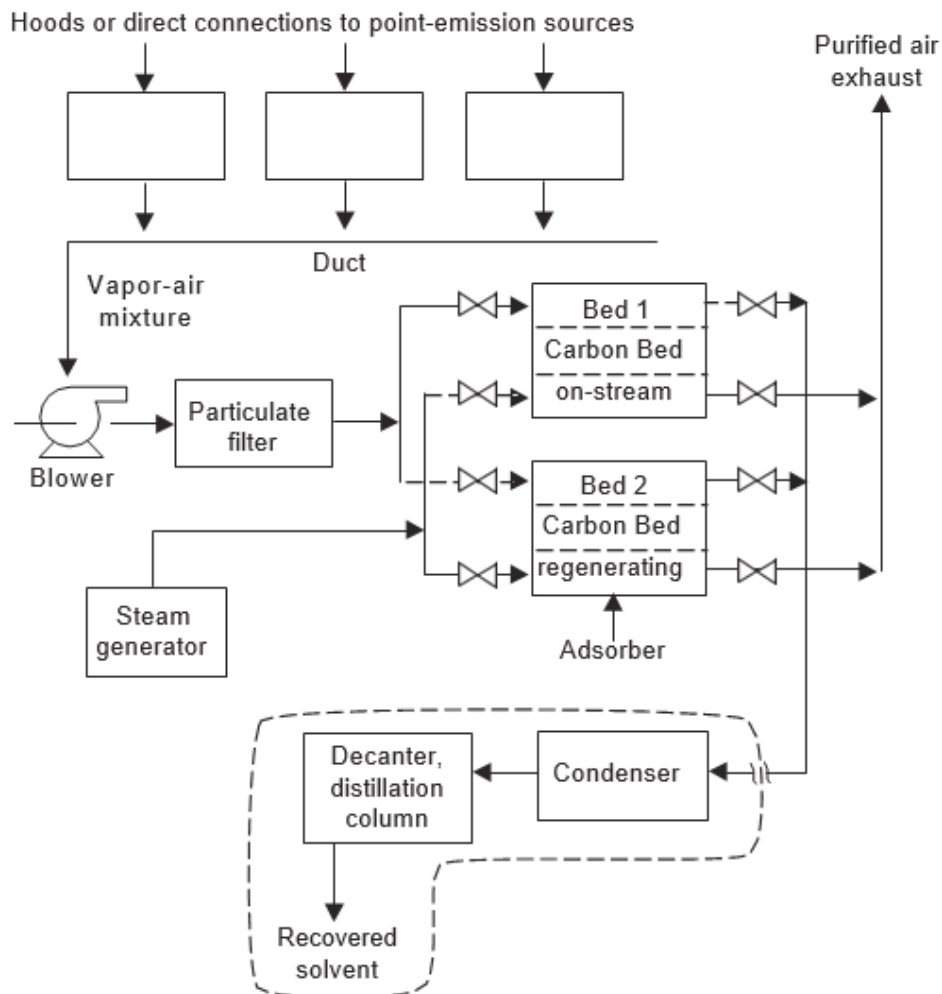


Figure 1.1: Typical-Two-Bed, Continuously Operated Fixed Bed Carbon Adsorber System

Cannister Units

Cannisters refer to relatively small returnable containers (like 55-gallon drums) used for lower-volume and intermittent streams where off-site regeneration is appropriate.

- **Regeneration:** Carbon cannisters are not intended for on-site desorption; they are replaced and returned to a central facility.
- **Series Operation:** Non-regenerable vessels can be placed in series to protect against breakthrough; the second vessel becomes primary once the first is saturated.
- **Monitoring:** Unlike fixed-bed units, cannisters are usually not monitored continuously; recordkeeping and vendor modeling are used to ensure frequent replacement.

Adsorption Theory

At equilibrium, gas quantity adsorbed on activated carbon is a function of temperature, pressure, chemical species, and carbon characteristics.

- **Adsorption Isotherm:** Relates the mass of adsorbate per unit weight of adsorbent (equilibrium adsorptivity) to the partial pressure of the VOC.
- **Type I Isotherms:** These shapes, convex upward throughout, are typical of adsorption on activated carbon.

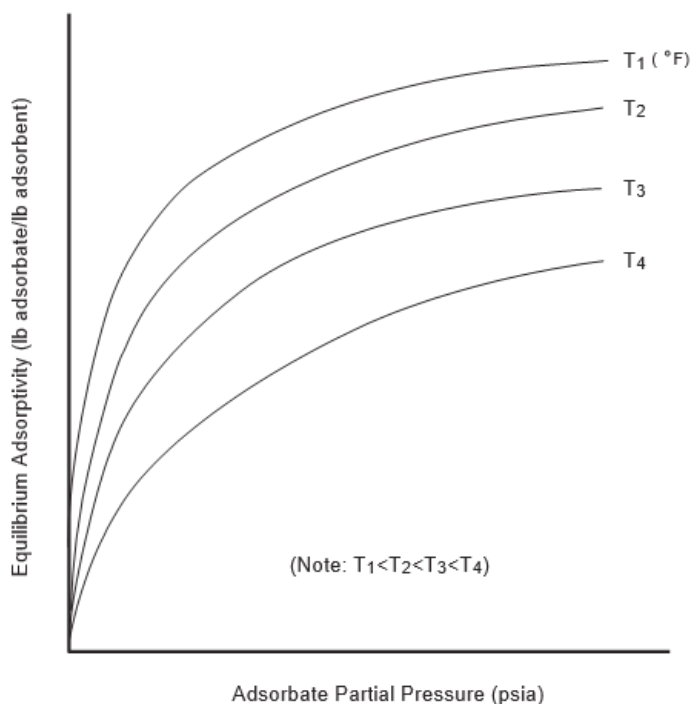


Figure 1.2: Type I Adsorption Isotherms for Hypothetical Adsorbate

Equation 1.1:

$$W_e = kP^m$$

Where:

- **W_e** = equilibrium adsorptivity (lb adsorbate/lb adsorbent)
- **P** = partial pressure of VOC in gas stream (psia)
- **k, m** = empirical parameters

Table 1.1: Parameters for Selected Adsorption Isotherms [6]^a

Adsorbate	Adsorption Temp (°F)	Isotherm Parameters		Range of Isotherm ^b (psia)
		<i>k</i>	<i>m</i>	
Benzene	77	0.597	0.176	0.0001-0.05
Chlorobenzene	77	1.05	0.188	0.0001-0.01
Cyclohexane	100	0.505	0.210	0.0001-0.05
Dichloroethane	77	0.976	0.281	0.0001-0.04
Phenol	104	0.855	0.153	0.0001-0.03
Trichloroethane	77	1.06	0.161	0.0001-0.04
Vinyl Chloride	100	0.200	0.477	0.0001-0.05
m-Xylene	77	0.708	0.113	0.0001-0.001
	77	0.527	0.0703	0.001-0.05
Acrylonitrile	100	0.935	0.424	0.0001-0.015
Acetone	100	0.412	0.389	0.0001-0.05
Toluene	77	0.551	0.110	0.001-0.05

^a Each isotherm is of the form $W = kP^m$. (See text for definition of terms.) Data are for adsorption of Calgon type "BPL" carbon.

^b Equation should not be extrapolated outside these ranges.

Design Tip: VOCs with lower vapor pressures will typically displace those with higher vapor pressure on the carbon surface. Base adsorption requirements on the least adsorbable component and desorption on the most adsorbable component.



Design Procedure

Sizing Parameters

Size and cost primarily depend on: (1) volumetric flow rate, (2) inlet/outlet mass loadings, (3) adsorption time, (4) carbon working capacity, and (5) gas humidity.

Determining Adsorption and Desorption Times

The configuration establishes the cycle profile, which determines vessel and utility requirements.

Equation 1.10:

$$M_c = M_{CI}f$$

Where:

- **M_c, M_{CI}** = carbon for continuous or intermittent control (lbs)
- **f** = extra capacity factor

Equation 1.11:

$$f = 1 + \frac{N_D}{N_A}$$

Where:

- **N_D** = number of beds desorbing
- **N_A** = number of beds adsorbing

Equation 1.12:

$$\theta_D \leq \frac{\theta_A N_D}{N_A}$$

Where:

- **θ_D** = total regeneration time (hours)
- **θ_A** = adsorption time



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