Carbon Adsorption for VOCs

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Module 1: Carbon Adsorbers

Learning Objectives

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

- **Identify** the physical and chemical principles of carbon adsorption and chemisorption for VOC removal.
- **Select** the appropriate adsorber type (fixed-bed vs. cannister) based on gas flow rates and VOC concentrations.
- **Calculate** the carbon requirement and sizing parameters for both continuous and intermittent operation modes.

Executive Summary: Carbon adsorption is a high-efficiency technology for removing volatile organic compounds (VOCs) from gas streams by capturing molecules on the surface of an adsorbent, primarily activated carbon. System design requires balancing volumetric flow, VOC loading, and adsorption cycle times to optimize both capital investment and annual operating costs.

Design Fundamentals

In air pollution control, **adsorption** is the preferred method for removing VOCs from low to medium concentration gas streams when recovery is desired or stringent outlet limits must be met.

The Adsorption Phenomenon

- **Physical Adsorption**: Gas molecules migrate to the solid surface and are held by weak attractive forces, releasing a **heat of adsorption** that typically exceeds the heat of condensation.
- **Chemisorption**: Gases form actual chemical bonds with the adsorbent surface groups, making them much more difficult to desorb.
- **Capacity Factors**: Capacity increases with the gas phase concentration, molecular weight, diffusivity, polarity, and boiling point.

Desorption and Regeneration

Most adsorbates are removed by heating (steam or hot combustion gases) or by reducing pressure (vacuum desorption). Approximately **3% to 5%** of organics on virgin activated carbon are strongly physically adsorbed or chemisorbed and cannot be removed during standard regeneration.

Adsorber Configurations

While five types of adsorption equipment exist, the industry standard for air pollution control centers on **fixed-bed systems** and **cannister units**.

Fixed-Bed Units

These units are scalable for flows from several hundred to over **100,000 cfm** and can handle VOC concentrations up to **25% of the Lower Explosive Limit (LEL)**.

- **Intermittent Operation**: The unit adsorbs during source operation and desorbs while the source is offline.
- **Continuous Operation**: Utilizes multiple beds (typically two or more) so that at least one is always on-stream while others are in the **desorption cycle** (regeneration, drying, and cooling).

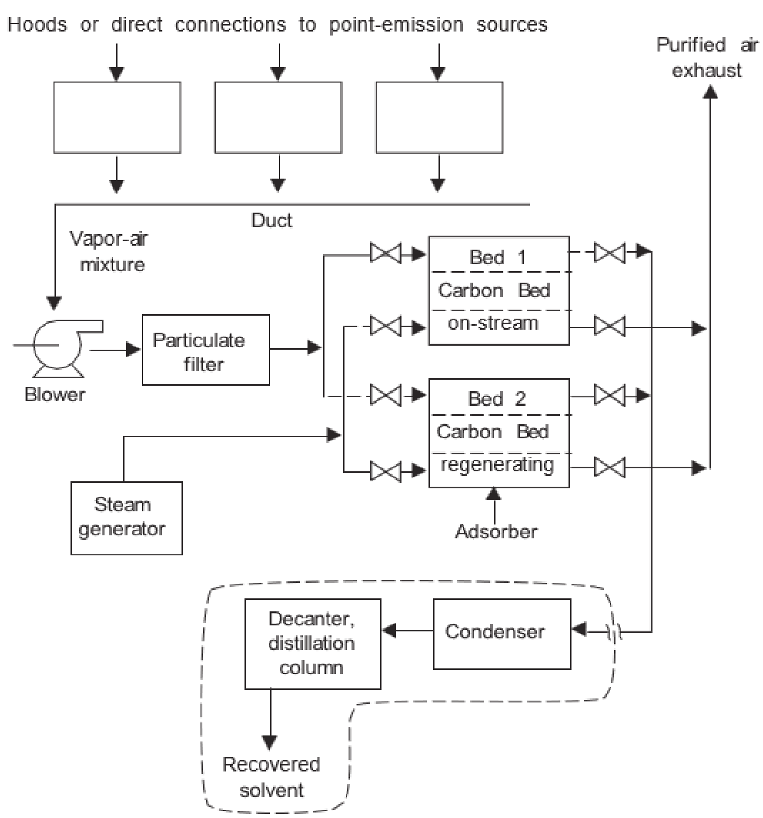

Figure 1.1: Typical-Two-Bed, Continuously Operated Fixed Bed Carbon Adsorber System

⚠️ **Safety Constraint**: Steam is the standard regenerant, but it **shall not** be used for halogenated VOCs (e.g., degreasing operations) as steaming may cause the VOCs to decompose.

Cannister Units

Originally referring to 55-gallon drums, these are now utilized for larger vessels up to **30,000 cfm** where on-site regeneration is not economically feasible.

- **Replacement Strategy**: Once saturated, the carbon or the entire cannister is replaced and sent to a central facility.
- **Breakthrough Protection**: Non-regenerable vessels can be placed in series; when the first becomes saturated, the second becomes the primary adsorber.

💡 **Design Tip**: Periodic sampling between carbon beds ensures replacement occurs before atmospheric breakthrough and improves cost-effectiveness by ensuring carbon is near saturation before disposal.

Adsorption Theory and Design

Designers rely on **adsorption isotherms** to relate equilibrium adsorptivity to the partial pressure of the VOC.

Sizing Parameters

System size and cost depend primarily on five variables:

1. Volumetric gas flow (acfm).
2. Inlet and outlet VOC mass loadings.
3. Adsorption time.
4. Working capacity of the carbon.
5. Gas stream humidity.

The Freundlich Isotherm

The **Freundlich Isotherm** is the standard power function used for industrial design.

Equation 1-1: We = k * P^m **Where:**

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

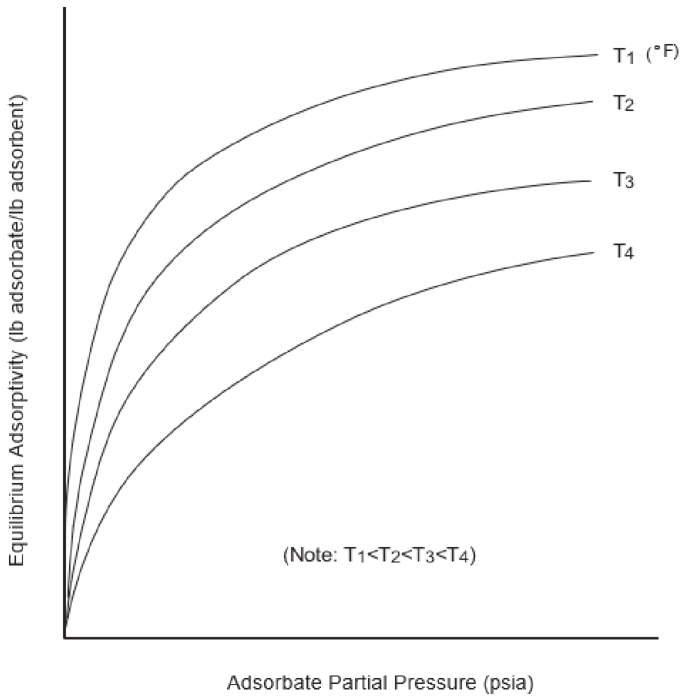

Figure 1.2: Type I Adsorption Isotherms for Hypothetical Adsorbate

Table 1.1: Parameters for Selected Adsorption Isotherms

Adsorbate	Adsorption Temp (°F)	Isotherm Parameters		Range of Isotherm[b] (psia)
		k	*m*	
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 for $W_e=kP^p$. (See text for definition of terms.) Data are for adsorption of Calgon type "BPL" carbon.
[b] Equation should not be extrapolated outside these ranges.

Carbon Requirement Estimation

The **working capacity (wc)** is the actual capacity used in design, which is a fraction of the equilibrium capacity.

Equation 1-14 (Continuous Systems): M = mvoc * qA * (1 + ND / NA) / wc **Where:**

- **M** = total system carbon charge (lbs)
- **mvoc** = VOC inlet loading (lb/h)
- **qA** = adsorption time (h)
- **ND** = number of desorbing beds
- **NA** = number of adsorbing beds
- **wc** = carbon working capacity (lb/lb)

🧮 **Calculation Note**: If specific working capacity data is unavailable, estimate **wc** at **50% of the equilibrium capacity** at the maximum inlet concentration.

Estimating Total Capital Investment (TCI)

TCI is derived from the **Purchased Equipment Cost (PEC)**, which is primarily driven by vessel size and carbon cost.

Vessel and Carbon Costs

- **Carbon Cost**: Calculated at approximately **$1.00/lb** (1999 dollars) for large systems.
- **Vessel Dimensions**: Sized based on superficial gas velocity, typically **60 to 85 ft/min**.

Equation 1-25 (Vessel Cost): Cv = 271 * S^0.778 **Where:**

- **Cv** = cost per vessel ($)
- **S** = vessel surface area (sq ft)