

Comprehensive Guide to Mass Transfer: Absorption and Extraction in Chemical Engineering

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The evolution of chemical engineering from a series of empirical industrial recipes to a rigorous scientific discipline is inextricably linked to the study of unit operations. Among these, **mass transfer** stands as a foundational pillar, governing the movement of chemical species from one phase to another. Two of the most critical processes within this domain are **absorption** and **extraction**. These processes are not merely theoretical concepts but are the backbone of modern industries ranging from petrochemical refining to pharmaceutical synthesis and environmental carbon capture.

The Legacy of Thomas K. Sherwood and the McGraw-Hill Series

To understand the depth of mass transfer, one must acknowledge the historical and technical contributions of **Thomas Kilgore Sherwood**. Sherwood, a former Dean of Engineering at MIT, was a pioneer whose work transformed the field. His seminal text, *Absorption and Extraction*, first published in 1937 as part of the McGraw-Hill Chemical Engineering Series, provided the first comprehensive, scientific treatment of these subjects. Before Sherwood, the design of absorption towers was often based on crude rules of thumb. Sherwood, along with collaborators like **Robert L. Pigford**, introduced rigorous mathematical modeling, leading to the development of the **Sherwood Number (Sh)**, a dimensionless number used in mass-transfer operations that relates convective mass transfer to diffusive mass transport.

The McGraw-Hill series itself represents a golden age of engineering literature, where complex physical phenomena were codified into actionable engineering principles. The second edition of the book expanded the scope to include more complex multi-component systems and more sophisticated liquid-liquid extraction methodologies, setting the standard for undergraduate and graduate education for decades.

Core Concepts of Gas Absorption

Gas absorption is a unit operation in which a gas mixture is contacted with a liquid (the solvent) for the purpose of preferentially dissolving one or more components of the gas. This creates a solution of the gas in the liquid. The reverse process, where a solute is removed from a liquid by contacting it with a gas, is known as **stripping** or desorption.

The Mechanisms of Mass Transfer

Mass transfer in absorption is typically described by the **Two-Film Theory**, proposed by Whitman in 1923. This theory assumes that:

- Two thin films exist on either side of the gas-liquid interface: a gas film and a liquid film.
- Resistance to mass transfer resides entirely within these films.
- The interface itself offers no resistance, and equilibrium exists at the contact surface.

The rate of absorption depends on the concentration gradient and the mass transfer coefficients. In mathematical terms, the flux (N) can be represented as:

$$N = k_g(P_g - P_i) = k_l(C_i - C_l)$$

Where k_g and k_l are the mass transfer coefficients for the gas and liquid phases, P represents partial pressure, and C represents concentration. Understanding these coefficients is vital for sizing industrial columns.

Equilibrium and Henry's Law

The extent to which a gas can be absorbed into a liquid is limited by the phase equilibrium. For dilute solutions, **Henry's Law** is the governing principle:

$$p = Hx$$

Where p is the partial pressure of the solute in the gas phase, x is the mole fraction in the liquid phase, and H is the Henry's Law constant. Factors affecting this equilibrium include temperature (solubility generally decreases as temperature increases) and pressure (solubility increases with higher partial pressure).

The Mechanics of Liquid-Liquid Extraction

While absorption involves gas and liquid phases, **liquid-liquid extraction** (or solvent extraction) involves the separation of components of a liquid mixture by treatment with a second, immiscible or partially miscible liquid solvent. This is a crucial operation when distillation is impractical—for instance, when components have similar boiling points or are heat-sensitive.

Solvent Selection Criteria

The success of an extraction process depends heavily on the choice of solvent. A Senior Technical Engineer must evaluate solvents based on several technical metrics:

- **Selectivity (Separation Factor):** The ratio of the distribution coefficients of the solute and the diluent. A higher selectivity indicates a more efficient separation.
- **Distribution Coefficient (K):** The ratio of the concentration of the solute in the extract phase to its concentration in the raffinate phase at equilibrium.
- **Insolubility:** The solvent should have low solubility in the feed liquid to minimize solvent loss and simplify downstream recovery.
- **Density Difference:** A significant difference in density between the phases is required for rapid phase separation by gravity.
- **Interfacial Tension:** If too high, it is difficult to disperse the liquids; if too low, the phases may emulsify and be impossible to separate.

Ternary Phase Diagrams

Engineering design for extraction often utilizes **ternary diagrams** (usually triangular graphs) to represent the equilibrium between the three components: the solute, the diluent (original carrier liquid), and the solvent. These diagrams help visualize the *plait point* and the *binodal curve*, which defines the limits of miscibility.

Technical Comparison: Absorption vs. Extraction

To assist in process selection, the following table compares the operational characteristics of these two unit operations.

Feature	Gas Absorption	Liquid-Liquid Extraction
Phase Contacted	Gas and Liquid	Liquid and Liquid
Primary Driver	Solubility in solvent	Relative solubility (Partitioning)
Mass Transfer Mechanism	Diffusion across gas-liquid film	Diffusion across liquid-liquid film
Common Equipment	Packed towers, Plate columns	Mixer-settlers, Centrifugal extractors
Key Design Variable	Gas velocity, L/G ratio	Solvent-to-Feed (S/F) ratio
Regeneration	Often via thermal stripping	Usually via distillation of extract
Primary Resistance	Usually gas film or liquid film	Often liquid film (slower kinetics)

Mathematical Modeling: The Sherwood Number and Correlations

In the text by **Sherwood and Pigford**, significant emphasis is placed on dimensionless analysis to predict mass transfer coefficients. The **Sherwood Number (Sh)** is defined as:

$$Sh = (k * L) / D$$

Where:

- k = mass transfer coefficient (m/s)
- L = characteristic length (m)
- D = mass diffusivity (m²/s)

For flow in pipes or over packing, the Sherwood number is often correlated with the **Reynolds Number (Re)** and the **Schmidt Number (Sc)**. For example, the Gilliland-Sherwood correlation for mass transfer in a wetted-wall column is:

$$Sh = 0.023 * Re^{0.83} * Sc^{0.44}$$

These correlations allow engineers to transition from lab-scale experiments to industrial plant design with a high degree of confidence.

Industrial Equipment and Hardware Design

Designing the physical vessels for these operations requires balancing efficiency with pressure drop and cost.

Packed Towers

Packed towers are used for both absorption and extraction. They are filled with "packing" material (e.g., Raschig rings, Pall rings, or structured packing) to provide a large surface area for contact. **Structured packing** offers higher efficiency and lower pressure drop than **random packing**, though at a higher capital cost.

Plate Columns

Plate or tray columns (bubble-cap, sieve, or valve trays) are common in large-scale absorption. Each tray acts as a discrete equilibrium stage. The number of actual trays required is calculated by taking the number of theoretical stages and dividing by the **Murphree tray efficiency**.

Mixer-Settlers and Centrifugal Extractors

In extraction, mixer-settlers are the simplest equipment, consisting of a stirred tank followed by a gravity settling chamber. For processes requiring rapid separation or dealing with liquids of similar densities, **centrifugal extractors** use high G-forces to achieve separation in seconds.

Practical Implementation: A Step-by-Step Design Guide

When implementing an absorption system in a modern facility, engineers should follow this procedural workflow:

1. Characterize the Feed Stream: Determine the flow rate, temperature, pressure, and exact chemical composition of the gas mixture.
2. Select the Solvent: Evaluate solvent capacity, cost, toxicity, and ease of regeneration.
3. Determine Equilibrium Data: Utilize Henry's Law constants or experimental VLE (Vapor-Liquid Equilibrium) data.
4. Calculate Minimum Solvent Rate: Determine the minimum L/G ratio to avoid reaching equilibrium at the column exit (operating line must not touch the equilibrium curve).
5. Choose Column Type: Decide between packing or trays based on pressure drop constraints and liquid loading.
6. Determine Column Diameter: Calculate based on "flooding velocity" (typically 60-80% of flooding).
7. Determine Column Height: Calculate the Height of a Transfer Unit (HTU) and the Number of Transfer Units (NTU). Total Height = HTU × NTU.

Case Study: Carbon Capture via Amine Absorption

A contemporary application of the principles laid out in *Absorption and Extraction* is the removal of CO₂ from flue gas using aqueous amine solvents (like MEA - Monoethanolamine). This is a **reactive absorption** process.

The Challenge

Flue gas contains roughly 12-15% CO₂ at low pressure. Physical absorption is inefficient here because the partial pressure is too low for significant solubility.

The Technical Solution

Engineers use a chemical solvent (MEA) that reacts exothermically with CO₂. This shifts the equilibrium significantly, allowing for high removal rates. However, this introduces new complexities: **heat of reaction**. The absorption tower becomes warmer as gas is absorbed, which in turn reduces the equilibrium capacity. This requires the use of intercoolers within the absorption column to maintain high efficiency.

Operational Troubleshooting

A common failure mode in amine units is **foaming**. Foaming increases the gas velocity locally, leading to liquid entrainment and eventually **flooding**. Solutions include:

- Installing high-efficiency carbon filters to remove degradation products.
- Injecting anti-foaming agents.
- Reducing the gas flow rate (though this impacts throughput).

Future Trends: Intensification and Sustainability

The legacy of Sherwood's work continues into the era of **Process Intensification (PI)**. Technologies such as **Rotating Packed Beds (RPB)** use centrifugal force to create extremely thin liquid films, significantly increasing the

mass transfer coefficient (k). This allows for absorption towers that are 10 times smaller than traditional vertical columns, reducing both footprint and capital expenditure.

Furthermore, in the realm of extraction, the shift toward **Green Solvents** like ionic liquids and deep eutectic solvents is reducing the environmental footprint of chemical processing. These solvents are non-volatile and can be tailored for specific selectivities, embodying the precision engineering that Thomas Sherwood advocated for nearly a century ago.

Summary of Engineering Principles

Mastering absorption and extraction requires a dual understanding of molecular-level transport and macro-scale hydraulics. By applying the dimensionless analysis pioneered by Sherwood, engineers can predict the behavior of complex systems. Whether it is removing H₂S from natural gas or recovering antibiotics from a fermentation broth, the core principles remain the same: optimize the interface, maximize the concentration gradient, and select the phase contactor that offers the best balance of efficiency and reliability.

As we look toward a future of decentralized manufacturing and carbon-neutral processes, the fundamental unit operations of absorption and extraction will remain indispensable tools in the chemical engineer's arsenal. The rigorous mathematical framework established in the 20th century provides the necessary foundation for the innovations of the 21st, ensuring that chemical processes remain safe, efficient, and sustainable.

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- [The Comprehensive Engineering Guide to Emulsion Formation, Stability, and Rheology](http://alghafgolden.com/guide-to-emulsion-formation-stability-rheology.pdf)

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- [Comprehensive Guide to Chemical Engineering Thermodynamics: Fundamentals, Equations of State, and Phase Equilibria](http://alghafgolden.com/comprehensive-guide-chemical-engineering-thermodynamics.pdf)

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