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MEMBRANE TECHNOLOGY

Engineering, design, and optimization of membrane processes for industry and research.

Diafiltration

1 Diafiltration

This article provides a practical introduction to diafiltration as a unit operation within ultrafiltration. In diafiltration, fresh solvent (water or buffer) is added to the membrane system while filtration is performed simultaneously. Low-molecular-weight substances (e.g., sugars) pass through the ultrafiltration membrane due to their small size, while macromolecules (e.g., proteins) are retained in the retentate due to the membrane cut-off (MWCO). By continuously adding fresh solvent (water or buffer) while removing permeate, low-molecular-weight components are washed out of the system.

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The amount of retained protein remains constant, while the concentration of small molecules decreases (depletion). This results in an increase in the *specific purity* of the protein in the retentate.

$$\text{specific purity} = \frac{m_{\text{target protein}}}{m_{\text{substances}}} \tag{1}$$

1.1 Product Purification

Diafiltration can be used to remove small molecules from a solution as completely as possible, transferring them into the permeate.

A: Product Recovery
Product in the permeate. MWCO larger than the product. Goal: complete transfer into the permeate.

Alternatively, diafiltration can be used to separate a target component from low-molecular-weight impurities, where the target remains in the retentate.

B: Product Purification
Product in the retentate. MWCO smaller than the product. Goal: removal of impurities.

In continuous diafiltration, the same amount of water or buffer Q_{DF} is continuously added to the tank as permeate Q_P is removed. As a result, the system volume V_S (tank + piping + membrane module) remains constant throughout the process.

Small molecules (e.g., salts) pass through the membrane and are washed out. Large molecules (e.g., proteins) are retained and remain in the system. Since the protein is retained and does not pass into the permeate, its total mass remains constant during diafiltration. In contrast, salts pass through the membrane and are continuously removed, leading to a steady decrease in their concentration in the system.

1.2 Retention

Retention R describes how strongly a component is retained by the membrane.

$$R = 1 \quad \text{(complete retention)} \tag{2}$$

If $R = 1$, the component is fully retained. In this example, this applies to the protein, which remains entirely in the system and does not enter the permeate.

$$R = 0 \quad \text{(no retention)} \tag{3}$$

If $R = 0$, the component passes completely through the membrane. In this example, this applies to salts, which fully transfer into the permeate.

If $R = 0$, the concentration in the permeate equals the system concentration at any time t:

$$c_P(t) = c_S(t) \tag{4}$$

If partial retention exists ($0 < R < 1$), the permeate concentration is lower than in the system:

$$c_P = (1 - R)\, c_S \tag{5}$$

1.3 Diafiltration Factor

The total volume of water (or buffer) added during diafiltration is called the diafiltration volume V_{DF}.

$$V_{DF} = \text{total added wash volume} \tag{6}$$

This volume can be related to the system volume V_S. The ratio is called the *diafiltration factor* D.

$$D = \frac{V_{DF}}{V_S} \tag{7}$$

A diafiltration factor of $D = 2$ means that a total volume equal to twice the initial system volume has been added.

1.4 Concentration Decay

The efficiency of diafiltration depends on retention R and diafiltration factor D.

Removal of low-molecular-weight components improves when:

- retention R is low, and
- diafiltration factor D is high.

This means small molecules are removed most effectively when they pass easily through the membrane ($R \approx 0$) and sufficient wash volume is applied (large D). The concentration c_S of a fully or partially permeable component decreases exponentially under constant-volume diafiltration:

$$\frac{c_S}{c_0} = e^{-D(1-R)} \tag{8}$$

where:

- c_0 is the initial concentration
- c_S is the concentration during or after diafiltration
- R is the retention of the component

1.5 Example

A system contains $V_S = 5000\,\text{L}$. A wash volume of $V_{DF} = 5000\,\text{L}$ is added.

$$D = \frac{5000}{5000} = 1 \tag{9}$$

Case 1: Salt ($R = 0$)

$$\frac{c_S}{c_0} = e^{-1} = 0.368 \tag{10}$$

The salt concentration decreases to 36.8% of its initial value.

Case 2: Product ($R = 0.95$)

$$\frac{c_S}{c_0} = e^{-1(1-0.95)} = e^{-0.05} = 0.951 \tag{11}$$

The product concentration remains at 95.1% of its initial value.

1.6 Average Permeate Concentration

The average concentration in the collected permeate is:

$$\frac{c_P}{c_0} = \frac{1 - e^{-D(1-R)}}{D(1-R)} \tag{12}$$

1.7 Yields

Yield can refer to two aspects:

- efficiency of washing out an undesired component
- recovery of a desired component

Yield in the retentate:

$$\eta_S = e^{-D(1-R)} \tag{13}$$

Yield in the permeate:

$$\eta_P = 1 - e^{-D(1-R)} \tag{14}$$

$$\eta_S + \eta_P = 1 \tag{15}$$

2 Multistage

In multistage continuous diafiltration, the feed stream is continuously diluted with water and passed through successive ultrafiltration units. Each stage removes low-molecular-weight components while retaining larger molecules. By repeating dilution and filtration, impurities are efficiently removed while maintaining high product yield.

Such systems are particularly suitable for large-scale continuous operation where consistent product quality is required.

3 Countercurrent Operation

To reduce water consumption, multistage diafiltration systems can be operated in countercurrent mode. In this configuration, permeate from downstream stages is reused as dilution liquid in upstream stages. This allows multiple reuse of water before discharge, significantly reducing fresh water demand while maintaining separation efficiency.

4 Water Recycling

In large-scale diafiltration systems, water consumption can be significant. To reduce fresh water usage, permeate can be treated using reverse osmosis (RO) or nanofiltration (NF). These additional membrane steps remove dissolved components, producing clean water that can be reused in the diafiltration process.

This approach improves resource efficiency and enhances process stability by removing unwanted substances from the system.