

tates. This method is effective for proteins with high surface hydrophobicity (that is, a nonpolar surface). It is inexpensive, but low pH values may result in the denaturation of proteins.

The use of ionic polyelectrolytes, such as ionic polysaccharides, polyphosphates, and polyacrylic acids, changes the ionic strength of the media and causes protein precipitation. However, polyelectrolytes may cause protein denaturation and structural damage.

The use of nonionic polymers, such as dextrans and polyethylene glycol, reduces the amount of water available to interact with protein molecules and results in protein precipitation. High concentrations of polymers are most effective for low-MW proteins, and nonionic polymers do not interfere with further protein recovery.

#### 11.4.4. Adsorption

*Adsorption* of solutes from liquid media onto solids is a common practice in separating soluble materials from fermentation broth. Various mechanisms may be involved in adsorption. In physical adsorption, weak forces, such as van der Waals forces, are dominant; however, in ion-exchange adsorption, strong ionic bonds are utilized. Solute is transferred from liquid to solid phase, and an equilibrium is reached after a while in a batch operation. The type of adsorbent used depends on the particular application. The most widely used adsorbent for waste-water treatment applications is activated carbon, since it has large internal surface area per unit weight. Ion-exchange resins and other polymeric adsorbents can be used for protein separations of small organics. For example, a carboxylic acid cation exchange resin is used to recover streptomycin. Adsorption capacity varies depending on adsorbent, adsorbate, physicochemical conditions, and the surface properties of the adsorbent and adsorbate. Usually, the exact mechanism of adsorption is not well understood, and the equilibrium data must be determined experimentally.

One typical equilibrium relationship between solute concentrations in liquid and solid phases is

$$C_S^* = K_F C_L^{*(1/n)} \quad (11.42)$$

where  $C_L^*$  and  $C_S^*$  are equilibrium concentrations of the solute in liquid and solid phases.  $C_S$  is in units of mass of solute adsorbed per unit volume of resin. This relationship is an example of a type of Freundlich adsorption isotherm, with  $K_F$  and  $n$  being empirical parameters and  $n$  being greater than 1.

Various types of solid–liquid contactors have been developed for the adsorption of solutes. Among these are packed-bed, moving-bed, fluidized-bed, or agitated-vessel contactors. Packed- and moving-bed contactors are the most widely used, since the adsorption area per unit volume of reactor is the largest among the others. Analysis of adsorption phenomena in a *packed-bed* column is based on a differential material balance of the solution in the column.

$$U \frac{\partial C_L}{\partial Z} + \varepsilon \frac{\partial C_L}{\partial t} = -(1 - \varepsilon) \frac{\partial C_S}{\partial t} \quad (11.43)$$

where  $U$  is the superficial velocity of the liquid,  $\varepsilon$  the porosity of the bed, and  $C_L$  the concentration of the solute in the liquid phase.