The solvent and solute fluxes in this case are

$$N_1 = K_{p1}(\Delta P - \pi) \tag{11.60}$$

$$N_i = C_i(1-\sigma_i)N_1 + K'_{pi}\,\Delta C_i; \quad i \geq 2 \tag{11.61}$$

11.4.7. Ultrafiltration and Microfiltration

Membranes are widely used to separate solute molecules such as proteins on the basis of their size and to concentrate cells from fermentation broth. Membrane separations may be used to separate proteins after precipitation to remove many of the contaminants. Membranes can serve as a molecular sieve to separate solute molecules of different molecular size. Depending on molecular-size cutoff, different membranes can be used for the separation of different MW proteins. *Microfiltration* or *microporous filtration* (MF) is used to separate species, such as bacteria and yeast, that range from 0.1 to 10 μm in width. Ultrafilters are used for macromolecules with a molecule-weight range of 2000 to 500,000. All these membrane sieving methods (microfiltration, ultrafiltration, reverse osmosis) are based on the same driving force, namely pressure, but have some minor differences. Some *ultrafiltration* (UF) membranes have *anisotropic structure*. In an anisotropic membrane, a thin skin with small pores is formed on top of a thick, highly porous structure. The thin layer provides selectivity, while the thicker layer provides mechanical support. With newer membrane materials available, anisotropic membranes are used less frequently. *Microporous filters* are usually isotropic and may have an open, tortuous path structure, which causes particle entrapment within the filter, or may have well-defined pores of uniform size.

While most membranes in use are made from polymers, ceramic membranes have increased in popularity. Factors that affect choice of membrane materials are interactions with proteins, mechanical stability, chemical stability (especially to cleaning agents), biocompatibility, flux rates, ease of sterilization (e.g., thermal stability), and cost. Typical polymeric materials are cellulose acetate, nylon, polytetrafluroethylene (PTFE), polyvinyldine difluroide (PVDF), and polysulfone. Ceramic membranes have a high level of chemical resistance, can be steam sterilized, and have a much longer life time (ca. 10 yr) versus many polymeric membranes. Such membranes have high initial cost and, while mechanically strong, are sometimes brittle. The actual choice of membrane depends on the application, the composition of the feed stream, and required product characteristics.

UF and MF membranes are widely used in the pharmaceutical, chemical, and food industries for the separation of vaccines, fermentation products, enzymes, and other proteins. Ultrafiltration is an energy-efficient, economical separation method used to concentrate chemicals and biologicals at a high degree of purity.

Typical UF and MF operations are pressure-driven processes in which low-MW solutes and water pass through the filter and high-MW solutes are retained on the membrane surface. Therefore, a concentration gradient builds up between the surface of the membrane and the bulk fluid. This gradient results in concentration polarization. As a result, solute diffuses back from the membrane surface to the solution (Fig. 11.20). At steady state, the rate of convective transfer of solute toward membrane is equal to the rate