and r_e is the effective radius of rotation. Σ is equal to the surface area of the gravity settling basin whose separation performance is equal to that of a particular centrifuge.

For a tubular centrifuge, Σ is

$$\Sigma = \frac{2\pi L\omega^2}{g}\left(\frac{3}{4}r_2^2 + \frac{1}{4}r_1^2\right) \tag{11.24}$$

where L is the length of cylindrical separator, and r_1 and r_2 are inner and outer radii of centrifugation distance.

For a bowl centrifuge, Σ is

$$\Sigma = \frac{2\pi n'\omega^2}{3g\tan\phi'}(r_2^3 - r_1^3) \tag{11.25}$$

where n' is the number of separator bowls, and ϕ' is the angle of inclination of the side walls.

Assuming that the free settling velocities of particles are the same, the following equation can be used for the scale-up of centrifuges.

$$\frac{F_{c_2}}{F_{c_1}} = \frac{\Sigma_2}{\Sigma_1} \tag{11.26}$$

where F_{c_1} and F_{c_2} are the flow rates through the small and large centrifuges, respectively.

Cross-flow microfiltration processes (Section 11.4.8) have replaced centrifugation in many bioprocesses, particularly when it is essential to prevent the escape of cells into the atmosphere. This consideration is particularly relevant when the organism is genetically modified.

11.2.3. Coagulation and Flocculation

Coagulation and flocculation are usually used to form cell aggregates before centrifugation, gravity settling, or filtration to improve the performance of these separation processes. Coagulation is the formation of small flocs from dispersed colloids using coagulating agents, which are usually simple electrolytes. Flocculation is the agglomeration of these small flocs into larger settlable particles using flocculating agents, which are usually polyelectrolytes or certain salts, such as $CaCl_2$.

Simple electrolytes used in coagulation are acids, bases, salts, and multivalent ions, which are relatively inexpensive, but less effective than polyelectrolytes. Certain fine solid particles, such as clays, activated carbon, or silica, may serve as nucleation sites for coagulation. Polyelectrolytes used in flocculation are high-molecular-weight, water-soluble organic compounds, which can be either anionic, cationic, or nonionic.

The analysis of gravity sedimentation is based on Stokes's and Newton's laws and is similar to the analysis presented in the centrifugation section. Sedimentation is a critical feature in the activated waste-treatment process and has been applied in some schemes to stabilize a population of genetically engineered cells. A list of widely used flocculants and their dosage ranges is given in Table 11.1. The important parameters to be considered in flocculation are flocculant–coagulant concentration, concentration of colloidal cells,