Figure 6.21 Collision efficiencies in brownian coagulation. Variations for Hamaker's constant A, particle radii R_i/R_j, and ionic strength I.

Fluid shear

In the second transport process, collisions between particles occur because of bulk motion of the fluid in laminar shear. As for brownian diffusion, consider a j particle at the center of a coordinate system and the flow of liquid into a sphere of influence of radius $R_{ij} = R_i + R_j$ as in Fig. 6.22. The velocity of the fluid at a height z is given by $z(dv/dz)$, as the velocity gradient is uniform. Assume that the particles follow streamlines and consider the rate of fluid flow dq into the disc of thickness dz (or area dA)

$$dq = z\left(\frac{dv}{dz}\right)dA = z\left(\frac{dv}{dz}\right)2(R_{ij}^2 - z^2)^{1/2}\,dz \qquad (6.31)$$
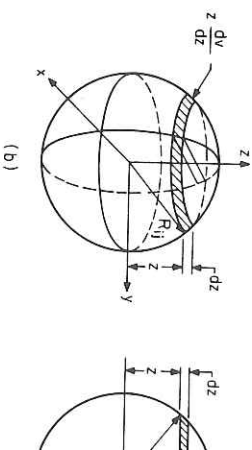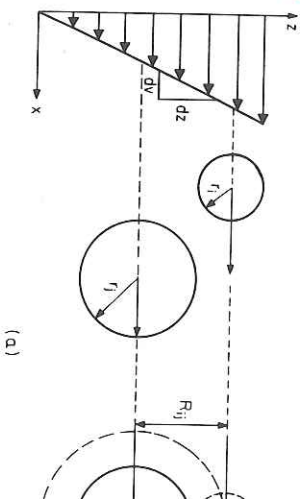

Figure 6.22 Schematic for Smoluchowski's theory of (a) velocity gradient and collision sphere; (b) flow; (c) areal projection in direction of flow.

$$= \frac{4}{3}n_i n_j (R_i + R_j)$$

Equation (6.33) is also expressed in terms and d_j and mean velocity gradient dv/dz
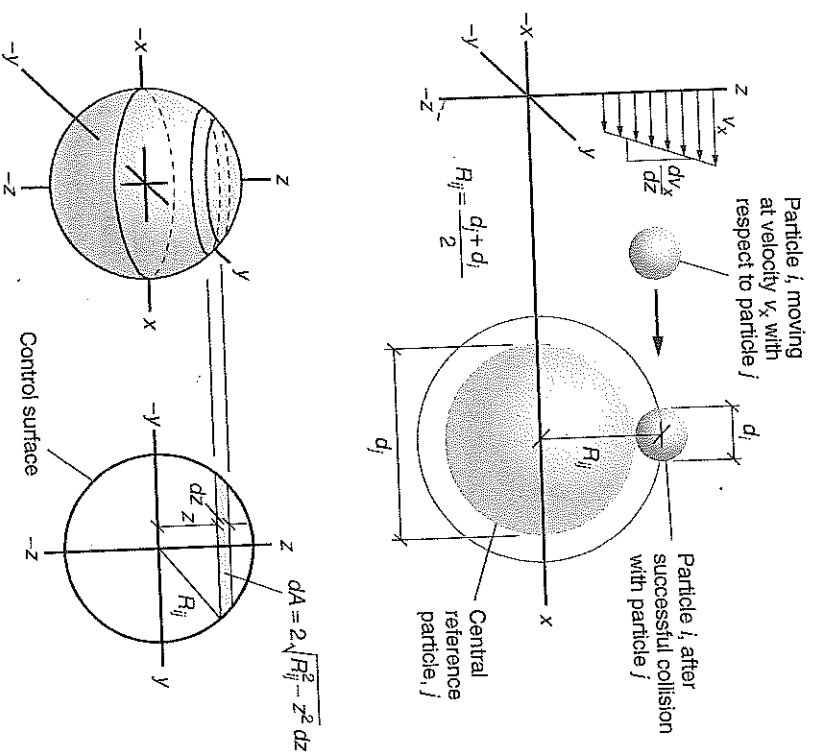
Figure 9-18
Definition sketch for analysis of the flocculation process.

Velocity gradients

When fluid flow is laminar and steady, the velocity gradients are well defined, as shown on Fig. 9-18. The velocity gradient on Fig. 9-18 is proportional to the shear stress on the fluid elements because it is a Newtonian fluid. Given a uniform velocity gradient, the rate of flocculation can be determined from geometric considerations, as illustrated below.

Rate of flocculation of heterodisperse particles

The rate of macroscale flocculation in a system of unequal size (heterodisperse) particles subjected to uniform mixing may be derived using the relationships shown on Fig. 9-18. The flow rate of fluid into an area element dA of the control surface is given by the following expression (Swift and Friedlander, 1964; Smoluchowski, 1917):

$$dq = (\text{velocity})(\text{differential area}) = \left(z\,\frac{dv_x}{dz}\right)\left(2\sqrt{R_{ij}^2 - z^2}\,dz\right) \qquad (9\text{-}30)$$
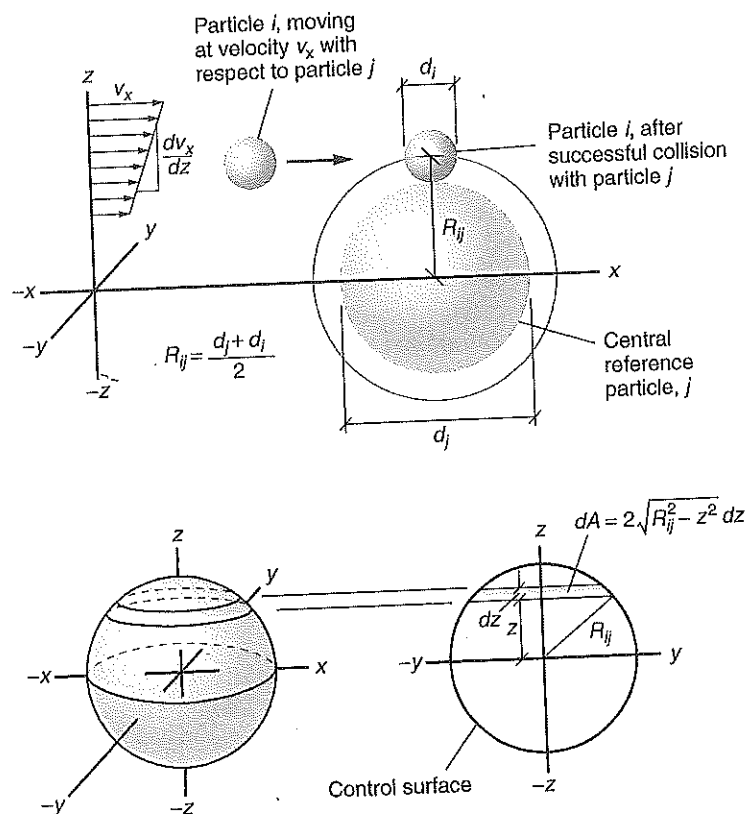
MuH, 3rd ed.

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Substituting Eq. 9-38 into Eq. 9-36 results in the following equation for the rate of flocculation of a monodisperse system:

$$r_M = \frac{4\Omega \overline{G} \alpha n_i}{\pi} \qquad (9\text{-}39)$$

Thus, the macroscale flocculation rate for a monodispersed suspension is a first-order rate expression with respect to n_i, and the rate constant is directly proportional to the velocity gradient and the floc volume fraction.

Rate correction for turbulent conditions
In practice, fluid flow in most flocculation units is turbulent. Under turbulent conditions, the velocity gradient is not well defined and will vary locally in the flocculation unit. As discussed in Sec. 6-10, Camp and Stein (1943) developed an expression relating $\overline{G}$ to mixing power (see Eq. 6-140) by equating the velocity gradients to the power dissipated per unit volume (P/V) for uniform shear flow:

$$\overline{G} = \sqrt{\frac{P}{\mu V}} \qquad (9\text{-}40)$$

where $\overline{G}$ = RMS velocity gradient, s^{-1}
P = power of mixing input to flocculation basin, W (note 1 W = 1 kg·m²/s³)
V = volume of flocculation basin, m³
μ = dynamic viscosity of water, kg/m·s

In turbulent flow, the rate of aggregation for particles smaller than the Kolmogorov eddy size (see Eq. 6-136) is approximately the same as it is for laminar flow because flow within eddies is laminar. Using this argument, the flocculation rate for turbulent shear should be similar to the rate for laminar flow. While this may be true in theory, it has been found that the rate is much higher due to interactions between eddies (Logan, 1999). Consequently, the rate becomes proportional to $\overline{G}$ (Harris et al., 1966), and an empirical rate constant must be employed, shown below for the monodisperse system:

$$r_{M,T} = K_A \overline{G} \Omega n_i \qquad (9\text{-}41)$$

where $r_{M,T}$ = rate of flocculation for turbulent flow
K_A = empirical aggregation constant

The aggregation constant depends on system chemistry, the heterogeneity of the suspension, and variations in the scale and intensity of turbulence, which are not incorporated in the velocity gradient. Because of the different flow patterns and distributions of velocity gradients promoted by various mixing devices, K_A must be determined experimentally.

t), and fine sand have all been used as coag-
are often added to waters that contain low
o form nucleating sites for the formation of
re used in conjunction with inorganic coagu-
, or both. Because the density of these particles
c particles, the settling velocities of flocculated

harged organic polymers that were discussed
used as flocculant aids as opposed to primary
cussed, the main advantage of using flocculant
s formed. Flocculant aids are added after the
ne particles are already destabilized. The time
depends on water temperature and the type
ar tests have to be conducted. The important
nated in jars and full-scale implementation are
ling rate. It should be noted that improper
n cause mudballs to form in gravity filters that
backwashing.

ortant inorganic flocculant aid that is used in
can be effective in cold water. It is usually stored
soluble at high pH. Usually, the concentrated
neutralized (usually with sulfuric acid) prior
mmediately to the water. In some instances,
re alum is the primary coagulatant because the
sed to activate the silica, and this will produce
nd the SiO_2 flocculant aid. A typical dosage is
.

eting reactions and mechanisms that are oper-
ocess, the selection of coagulants and dosage is
ically using bench-scale and pilot-scale studies.
testing procedure for determining coagulant
jar test" procedure. Developed originally by
ed over the years (see Black et al., 1957; Tekippe
permits rapid evaluation of a range of coagulant
jar test apparatus is shown on Fig. 9-12. As shown
s consists of six batch reactors, each equipped
-shaped jars are used to avoid vortex flow, which
rs are used.

Figure 9-12
Jar test apparatus. Note use of square containers to limit the formation of vortex flow in which the particles rotate in the same position relative to each other.

jar testing procedures are available in Kawamura (2000), ASTM (2008), and AWWA (2011). Generally, the test consists of a rapid-mix phase (blending) with simple batch addition of the coagulant or coagulants followed by a slow-mix period to simulate flocculation. Flocs are allowed to settle and samples are taken from the supernatant. These parameters should be measured as part of the jar test routine: (1) turbidity or suspended solids removal; (2) NOM removal as measured by dissolved organic carbon (DOC) or a surrogate measure of dissolved NOM, such as UV at 254 nm; (3) residual dissolved coagulant concentrations of Fe or Al coagulants; and (4) sludge volume that is produced. If direct filtration is to be used, the filterability should be evaluated using a filterability test. The filterability is evaluated by filtering the mixed suspension through a 5- or 8-μm laboratory filter to simulate a granular medium filter.

The results of a series of jar tests to determine the optimum alum dose and pH for turbidity removal for given water are summarized on Fig. 9-13. As shown on Fig. 9-13, the optimum alum dose and pH would be approximately 8 mg/L and 7, respectively, because the turbidity is minimized under these conditions. However, it must be emphasized that the raw-water particle concentration and NOM vary with water quality, and thus the optimum coagulant dosage also changes as the water quality changes.

ANALYSIS OF COAGULATION PROCESS USING JAR TEST PROCEDURE
A conceptual diagram in which the residual turbidity from jar tests conducted for waters with different particle concentrations is illustrated on

is higher, then no cationic metal ion species would be formed for charge neutralization. Furthermore, the impact of NOM on the coagulant dose has not been considered.

Water with low concentration of particles

For the lowest particle concentration, S_1, particles are removed by sweep flocculation (precipitation) because the concentration is too low for them to flocculate and settle. These particles are also destabilized by the hydrolysis products of the coagulant. The particle concentration S_1 may be a good candidate for direct filtration or dissolved air flotation for liquid–solid separation.

Water with moderate concentration of particles

At a slightly higher particle concentration, S_2, some flocculation and settling occurs in zone 2, in which adsorption and charge neutralization occur. However, the concentration is too low for effective flocculation and a high degree of turbidity removal is not possible. Further, if more coagulant is added, the particles stabilize with a positive charge and the turbidity increases, as shown in zone 3. However, as the coagulant dosage is increased even further, sweep flocculation is again observed but at a lower coagulant concentration than for a particle concentration S_1 because the particle concentration is higher, which allows for more effective flocculation and settling at a lower coagulant dosage.

Water with high concentration of particles

At a higher particle concentration, S_3, all four zones can clearly be found. Nearly complete removal by charge neutralization occurs in zone 2 and the particles stabilize at higher coagulant dosages. Sweep flocculation occurs in zone 4, and it occurs at lower coagulant dosages than for particle concentration S_2 or S_1. Sweep flocculation occurs because a substantial portion of the floc volume comes from the particles, and this allows for effective flocculation at lower coagulant dosages.

Water with very high concentration of particles

For the highest particle concentration, S_4, the sweep floc and charge neutralization regions merge because the coagulant concentration required to neutralize the charges on the particles coincides with the onset of precipitation. Another noteworthy effect is that zone 2 starts at successively higher coagulant dosages as the particle concentration increases. As a result, the charge neutralization region is said to exhibit stoichiometry.

Analysis of results
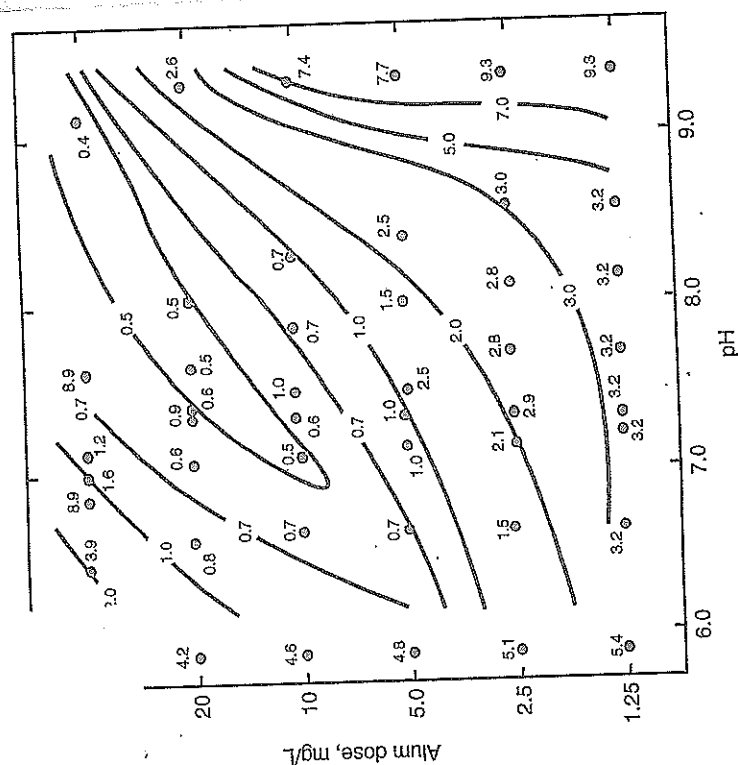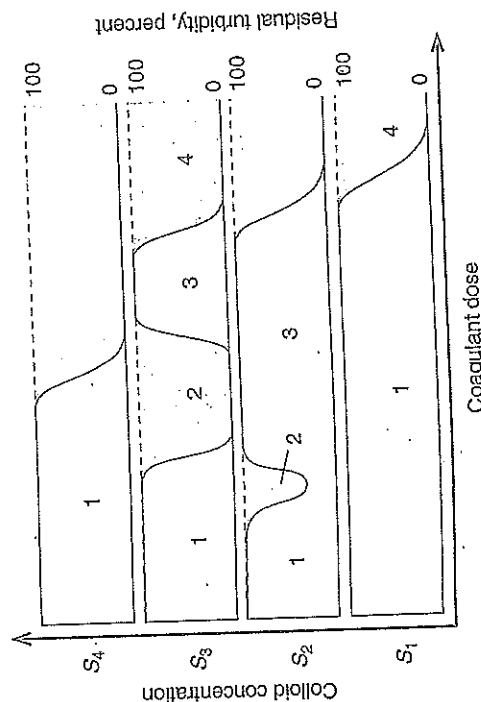
-14
d residual turbidity remaining after
as a function of particle and
t concentration for Al(III) or Fe(III)
constant pH. (Adapted from
1972.)