

Destabilization of Colloidal Suspensions

3.1 COLLOIDAL SUSPENSIONS

Many impurities in waters and wastewaters are present as colloidal dispersions, i.e. they occur in particulate form within the approximate size range 1 to 10^{-3} μm (refer Fig 1.3). Examples of this type of suspension include clays, substances of biological origin such as natural colour, proteins, carbohydrates and their natural or industrial derivatives. Invariably suspensions of this type possess an inherent stability or resistance to particle aggregation. They are not amenable to clarification by sedimentation due to their negligible settling velocity (refer Fig 2.2) nor can they be clarified by sand filtration processes. Their transformation to a flocculent condition is effected by the process of coagulation.

Colloidal particles have a very high specific surface and consequently their behaviour in suspension is largely determined by surface properties, the gravitational influence on movement being relatively unimportant. Colloidal particles may be hydrophobic (clays, metal oxides) or hydrophilic (plant and animal residues, proteins, starch, detergents).

Hydrophobic colloids have no affinity for water and are considered to derive their stability from the possession by individual particles of like charges, which repel each other. These charges may arise from the preferential adsorption of a single ion type on the particle surface or from the chemical structure of the particle surface itself. The possession of charge, positive or negative, by a colloid gives rise to its envelopment by an 'electrical double layer', resulting in a potential gradient in the particle vicinity, as shown in Fig 3.1.

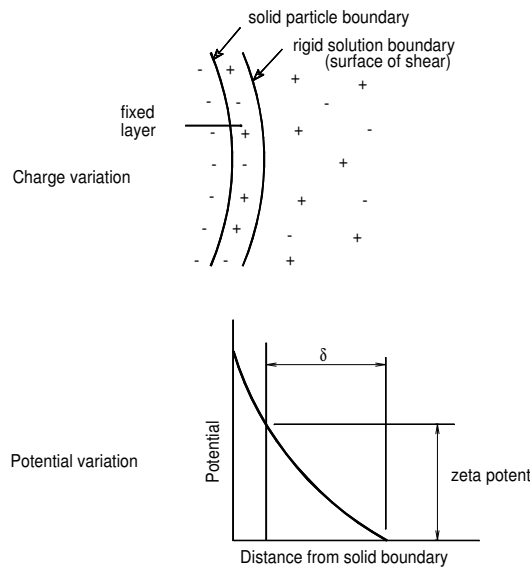


Fig 3.1 Charge and potential variation in the vicinity of a colloid surface

Since all particles in a given colloidal dispersion are similarly charged, such a suspension is stable by virtue of the electrostatic repelling forces which prevent particles coming together under the influence of Brownian motion and van der Waals attractive forces. It is not possible to measure the potential at the solid-particle boundary but the potential at the rigid-solution boundary or plane of shear can be measured. This latter is called the zeta potential (ζ) and is related to the particle charge and the double layer thickness as follows:

$$\zeta = 4\pi\delta q/D \quad (3.1)$$

where δ is the double layer thickness, q is the particle charge and D is the dielectric constant for the liquid medium.

The zeta potential is determined experimentally in an externally applied electric field. The ordinary range of zeta potential is 20 to 200 mV (Fair et al., 1968). Optimum coagulation may be expected to occur when the zeta potential has been reduced to zero (the isoelectric condition of the suspension). For effective coagulation it is necessary to reduce the zeta potential to within 0.5 mV of the isoelectric point (Stumm and Morgan, 1962).

Hydrophilic colloids have, as their name implies, a marked affinity for water. Their stability is due mainly to bound water layers which prevent close contact between particles, although charge is also considered to contribute to their stability. These mainly organic substances may be single macromolecules or aggregates of macromolecules and may be in true solution or suspension. They derive their charge from the ionisation of attached functional groups such as the carboxyl ($-\text{COO}^-$), hydroxyl ($-\text{OH}^-$), sulphato ($-\text{SO}_3^-$), sulphato ($-\text{SO}_3^-$), phosphato ($-\text{PO}_3\text{H}^-$) and amino ($-\text{NH}_3^+$) groups. The magnitude of this charge is dependent upon the extent of ionisation of the functional groups, which, in turn, is influenced by the pH of the medium. The charge also influences the solubility of hydrophilic colloids, the minimum solubility being frequently found to coincide with the isoelectric point, which in the majority of cases lies within the pH range 4.0-6.5.

Hydrophilic colloids may become absorbed on hydrophobic colloidal particles such as clays, thereby imparting hydrophilic properties to the latter. Colloidal suspensions of this kind are called 'protective colloids' and may be difficult to coagulate.

3.2 COAGULATION

Coagulation, or the destruction of colloidal stability, may be effected in four major ways: (i) boiling; (ii) freezing; (iii) mutual flocculation by addition of a colloid of opposite charge; and (iv) the addition of electrolytes. Of these only the latter is of major significance in water and wastewater engineering practice.

Boiling a hydrophobic colloidal suspension may sometimes effect coagulation, mainly through a reduction in the extent of hydration of the colloidal particles and an increase in their kinetic energy. Freezing a colloidal suspension may likewise effect its coagulation by increasing the concentration of the dispersed phase and the ion concentration of the dispersing phase through the growth of ice crystals. Freezing has been proposed as a means of improving the dewatering characteristics of sludges and is also used in the vegetable processing industry for the same purpose.

Complete mutual precipitation occurs when colloids of opposite charge are mixed in equivalent amounts in terms of electrostatic charge. This method is not used per se in water and wastewater treatment practice but may occur to some extent in coagulation with iron and aluminium salts.

3.2.1 Effects of electrolytes

Added electrolytes may be considered to act in two ways that tend to reduce zeta potential and hence the stability, particularly of hydrophobic colloids. By increasing the ionic strength of the dispersing medium they reduce the double layer thickness, while the adsorption of ions of opposite charge by a colloid reduces its own net charge. This influence of added electrolyte charge on colloid stability is shown graphically in Fig 3.2. It has been found that the effectiveness of added ions of opposite charge increases dramatically with their valency, a finding first observed by Schulze and Hardy and often expressed as the Schulze-Hardy rule, which states: 'the precipitation of a colloid is effected by that ion of an added electrolyte which has a charge opposite in sign to that of the colloidal particles, and the effect of such ion increases markedly with the number of charges it carries'. The relative coagulating power of a number of electrolytes is shown in Table 3.1.

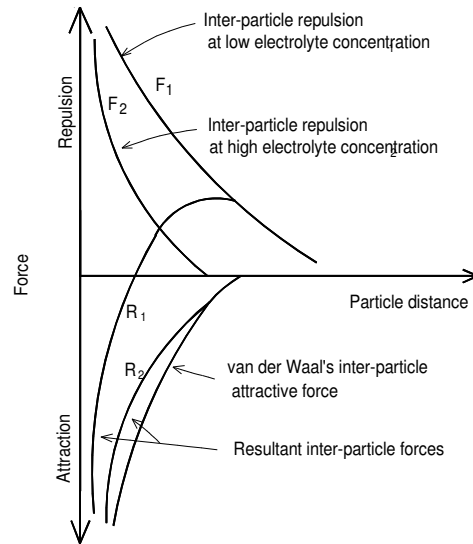


Fig 3.2 Influence of electrolytes on colloid stability (Fair et al., 1968)

Table 3.1 Effectiveness of coagulants

Electrolyte	Relative power of coagulation	
	Positive colloids	Negative colloids
NaCl	1	1
Na ₂ SO ₄	30	1
Na ₃ PO ₄	1000	1
BaCl ₂	1	30
MgSO ₄	30	30
AlCl ₃	1	1000
Al ₂ (SO ₄) ₃	30	>1000
FeCl ₃	1	1000
Fe ₂ (SO ₄) ₃	30	>1000

Source: Sawyer and McCarthy (1967)

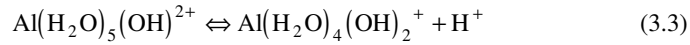
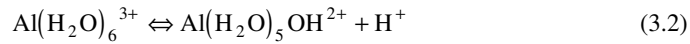
Two other mechanisms also contribute to colloid removal by chemical coagulation. These are (a) enmeshment by the hydroxo-metal precipitate formed by the coagulant chemicals and (b) inter-particle bridging. The enmeshment mechanism may be assumed to increase in significance with increasing coagulant dose and hence increasing volumetric concentration of enmeshing solid surface area. The inter-particle bridging mechanism is specifically associated with polyelectrolytes, which are discussed in section 3.4.

The most important coagulating chemicals in water and wastewater treatment are the trivalent salts of aluminium and iron. Their primacy as coagulants is due to (a) their effectiveness (see Table 3.1) in destabilizing the predominantly negatively charged colloids found in natural waters and wastewaters, (b) their low solubility levels in the pH range of normal use (see Fig 3.3) – this is of particular importance in the production of drinking water, and (c) their availability and relatively low cost.

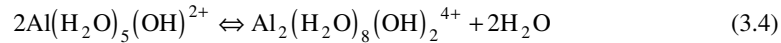
3.3 COAGULATION WITH IRON AND ALUMINIUM SALTS

The coagulating mechanisms of the trivalent salts of iron and aluminium have been widely studied and may be summarized in simplified terms as follows: (i) 'Free' trivalent aluminium and iron ions are

released in a solution of the respective salts. However, under coagulation conditions only relatively small concentrations of Al^{3+} and Fe^{3+} are present in solution and hence their influence on coagulation may not be as great as is sometimes suggested. (ii) Hydrated metal ions are hydrolysed, producing complex hydrated metal hydroxide ions:



A corresponding set of reactions could be written for trivalent iron. The equilibrium constants for some of these and other similar step reactions are given in Table 3.2. It is important to note that the pH of the solution is depressed by these hydrolytic reactions. Polymerisation may also occur:



It is thought that the extent of polymerisation increases with age – the dimer of equation (3.4) may undergo further hydrolytic reactions yielding higher hydroxide complexes, leading to the formation of positively charged colloidal polymers and ultimately to hydroxide precipitates. Both the positively charged complex ions and the colloidal hydroxo polymers are considered to play an important role in the overall mechanism of coagulation. (iii) The anions of the trivalent salts also play a part in completing the coagulation process by promoting the coagulation of any excess of positively charged metal hydroxo colloids formed. In this respect the greater coagulating power of divalent ions such as sulphates over monovalent ions such as chlorides may be significant.

Table 3.2 Hydrolysis and complex formation equilibria for iron and aluminium

Reaction	Log of equilibrium constant (25 °C)
$\text{Fe}^{3+} + \text{H}_2\text{O} \rightleftharpoons \text{FeOH}^{2+} + \text{H}^+$	-2.16
$\text{Fe}^{3+} + 2\text{H}_2\text{O} \rightleftharpoons \text{Fe}(\text{OH})_2^+ + 2\text{H}^+$	-6.74
$\text{Fe}(\text{OH})_3(\text{s}) \rightleftharpoons \text{Fe}^{3+} + 3\text{OH}^-$	-38
$\text{Fe}^{3+} + 4\text{H}_2\text{O} \rightleftharpoons \text{Fe}(\text{OH})_4^- + 4\text{H}^+$	-23
$2\text{Fe}^{3+} + 2\text{H}_2\text{O} \rightleftharpoons \text{Fe}_2(\text{OH})_2^{4+} + 2\text{H}^+$	-2.85
$\text{Al}^{3+} + \text{H}_2\text{O} \rightleftharpoons \text{Al}(\text{OH})^{2+} + \text{H}^+$	-5
$7\text{Al}^{3+} + 17\text{H}_2\text{O} \rightleftharpoons \text{Al}_7(\text{OH})_{17}^{4+} + 17\text{H}^+$	-48.8
$13\text{Al}^{3+} + 34\text{H}_2\text{O} \rightleftharpoons \text{Al}_{13}(\text{OH})_{34}^{5+} + 34\text{H}^+$	-97.4
$\text{Al}(\text{OH})_3(\text{s}) + \text{OH}^- \rightleftharpoons \text{Al}(\text{OH})_4^-$	1.3
$2\text{Al}^{3+} + 2\text{H}_2\text{O} \rightleftharpoons \text{Al}_2(\text{OH})_2^{4+} + 2\text{H}^+$	-6.3
$\text{Al}(\text{OH})_3(\text{s}) \rightleftharpoons \text{Al}^{3+} + 3\text{OH}^-$	-33

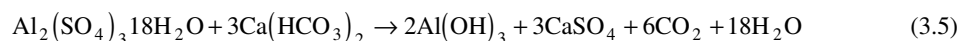
Source: Snoeyink and Jenkins (1980)

The range of aluminium and iron coagulant chemicals used in water and wastewater treatment is listed in Table 3.3. Aluminium sulphate or alum is the most widely used coagulant in drinking water production. Ferric sulphate is also a commonly used coagulant.

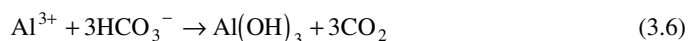
Table 3.3 Aluminium and iron salts used in coagulation

Chemical	Commercial form	Cation content
Aluminium sulphate (alum) (Al ₂ (SO ₄) ₃ ·18H ₂ O)	Liquid, SG 1.32	4.2% Al ³⁺ by weight
	Solid slab	7.4% Al ³⁺ by weight
	Kibbled solid	9.1% Al ³⁺ by weight
Poly-aluminium chloride (PACl) (Al _n (OH) _m Cl _{3n-m})	Liquid, SG 1.20	5.3% Al ³⁺ by weight
Poly-aluminium silicate sulphate (PASS) ?	Liquid, SG ?	4.4% Al ³⁺ by weight
Ferric sulphate (Fe ₂ (SO ₄) ₃)	Liquid, SG 1.55	11.2% Fe ³⁺ by weight
Ferric chloride (FeCl ₃)	Liquid, SG ?	? Fe ³⁺ by weight
Ferrous sulphate (copperas) (FeSO ₄ ·7H ₂ O)	?	?

When an aluminium coagulant chemical is added to water in the presence of alkalinity the overall reaction is as follows:



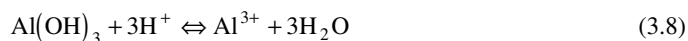
Omitting the non-reacting species, this reaction may be written as:



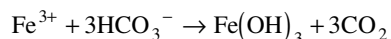
In stoichiometric terms, therefore, 1 mg l⁻¹ of alum removes 0.45 mg l⁻¹ of alkalinity (as CaCO₃) and releases 0.4 mg l⁻¹ CO₂. The presence of alkalinity acts as a buffer against excessive lowering of pH, the value of which has an important influence on coagulation. The aluminium hydroxide precipitate formed might be more correctly called a hydrated aluminium oxide precipitate:



It is amphoteric, in that it can react with H⁺ and OH⁻ ions, depending on pH:



The reaction of iron salts in water containing alkalinity is similar to that given above for alum, the net overall reaction being:



From the foregoing reactions and their equilibrium constants (Table 3.2) it is clear that aluminium and iron are soluble at high and low pH values. The principal ion species remaining in solution are:

Aluminium: Al³⁺, Al(OH)²⁺, Al₇(OH)₁₇⁴⁺, Al₁₃(OH)₃₅⁵⁺, Al(OH)₄⁻, Al₂(OH)₂₄⁺

Iron: Fe³⁺, FeOH²⁺, Fe(OH)₂⁺, Fe₂(OH)₂⁴⁺, Fe(OH)₄⁻

The solubilities of both metals are shown graphically in Fig 3.3 as a function of pH.

The achievement of a low residual ion concentration is particularly important in the production of drinking water. The maximum acceptable concentration for both metals is typically set at 200 mg l^{-1} (WHO, 2005, EU, 1998). As may be observed in Fig 3.3, the solubility of iron is less than this limit value in the narrower pH range 5.2-7.5. However, it is important to note that these solubility values are equilibrium concentrations and require an equilibrium condition to exist for their realisation. This may not always be the case in chemical coagulation practice. It has been observed, for example, that in the chemical coagulation of coloured waters using ferric sulphate, that the residual iron concentrations significantly exceed the solubility values presented in Fig 3.3, especially in the pH range below 5 (Black and Walters, 1964; Haarhoff and Cleasby, 1988; Carroll and Higgins, 1994). The solubility of aluminium in coagulation practice has been found to conform reasonably close to that indicated in Fig 3.3.

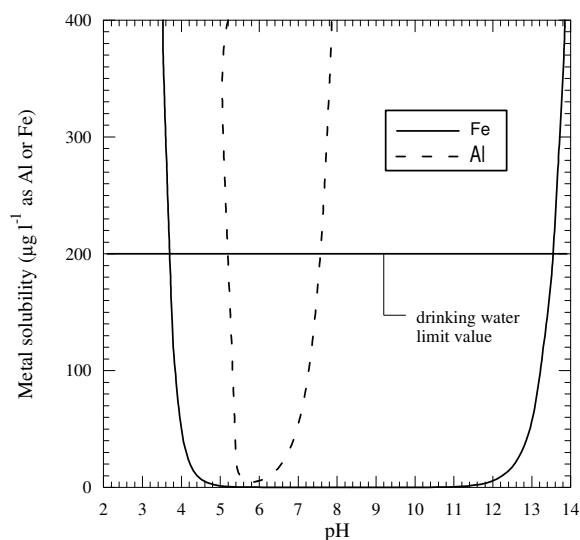
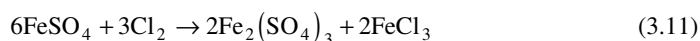


Fig 3.3 Solubility of iron and aluminium in water at 25 °C.

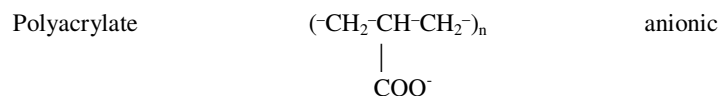
Ferrous sulphate, or copperas ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), is also sometimes used as a coagulant on its own or in combination with chlorine in the form of chlorinated copperas:



Other aluminium salts sometimes used in coagulation practice are sodium aluminate, NaAlO_2 , which is strongly alkaline in solution and may be used in conjunction with alum, and aluminium chlorohydrate, $\text{Al}_2\text{Cl}(\text{OH})_5$, sometimes used as a dewatering aid for sewage sludges.

3.4 POLYELECTROLYTES

Polyelectrolytes are polymers that contain functional groups, such as carboxyl, hydroxyl, amino and other groups. Owing to the presence of these charged sites they possess properties similar to ordinary low molecular weight electrolytes, e.g. they are soluble and conduct electricity. In solution they may be classified as hydrophilic colloids. Depending on their attached functional groups they may be anionic, cationic or ampholytic. Typical examples of each category are:



Polyvinylpyridinium	$(-\text{CH}_2-\text{CH}-\text{CH}_2)_n$	cationic
Polyamino acids	$(-\text{NH}-\text{CH}-\text{CO}-\text{NH}-\text{CH}-\text{CO}-)$ $\begin{array}{cc} & \\ (\text{CH}_2)_4 & (\text{CH}_2)_4 \\ & \\ (\text{NH}_3)^+ & \text{COO}^- \end{array}$	ampholytic

The mechanism of coagulation with polymers is considered to be mainly an adsorptive and bridging one, producing a loose interconnected network of flocs. Neutralization of charge may also be part of the mechanism, although it has been found that some polyelectrolytes are effective in coagulating colloidal dispersions carrying a charge of the same sign as that possessed by the polyelectrolyte.

In water and wastewater treatment practice polyelectrolytes are normally used in low concentrations as coagulant aids, usually in conjunction with trivalent iron or aluminium salts.

3.5 DETERMINATION OF THE REQUIRED COAGULANT DOSE

Because of the many factors that influence coagulation and the complex reactions involved, it is not feasible to calculate directly the coagulant dosage required for coagulation of a particular water or wastewater. An experimental jar test procedure (Cox, 1964). Using a multiple stirrer apparatus, simultaneous tests are carried out on a series of samples covering a range of coagulant concentration. On addition of the coagulant, the samples are rapidly mixed for 2 min, followed by slow mixing for 20 min. The samples are then allowed to stand for 60 min, after which the colour and turbidity of the supernatant water is measured and the lowest coagulant dose giving adequate removal noted. Using the latter concentration of coagulant a second similar set of tests is performed on pH-adjusted samples to determine the optimum for coagulation. Typical jar test results are shown in Figs 3.4 and 3.5. An alternative but similar jar test procedure, involving the use of zeta potential measurement in place of colour and turbidity, has also been used.

3.5.1 Flocculation

When a colloidal suspension has been destabilized, primary floc particles are formed and grow in size through contact with other particles as a result of Brownian motion. This process is sometimes called perikinetic flocculation. As particles grow in size the influence of Brownian motion effects is diminished and the rate of particle aggregation correspondingly reduced. To accelerate the rate of particle collision, velocity gradients are created within the body of the dispersing fluid. This controlled use of velocity gradients to promote flocculation is sometimes called orthokinetic flocculation.

3.5.2 The role of velocity gradient in flocculation

To form aggregates, colloidal particles must be brought sufficiently close together to come under the influence of their van der Waals forces of attraction. Consider any suspended particle having a radius of influence, as determined by the van der Waals force, of R_j . It will attract any other suspended particle i provided the centre of such particle comes within a distance of (R_j+R_i) of the centre of particle j , i.e. within a sphere of influence of radius (R_j+R_i) . Now consider a streamtube of radius $R = R_j+R_i$, with a velocity v at the centre and a constant velocity gradient in the z -direction as shown in Fig 3.6. The volume of fluid within the stream tube, which flows past particle j (located at the centre of the stream tube section) per unit time is given by

$$\text{vol./time} = 2 \int_0^R z \frac{dv}{dz} b dz \quad (3.12)$$

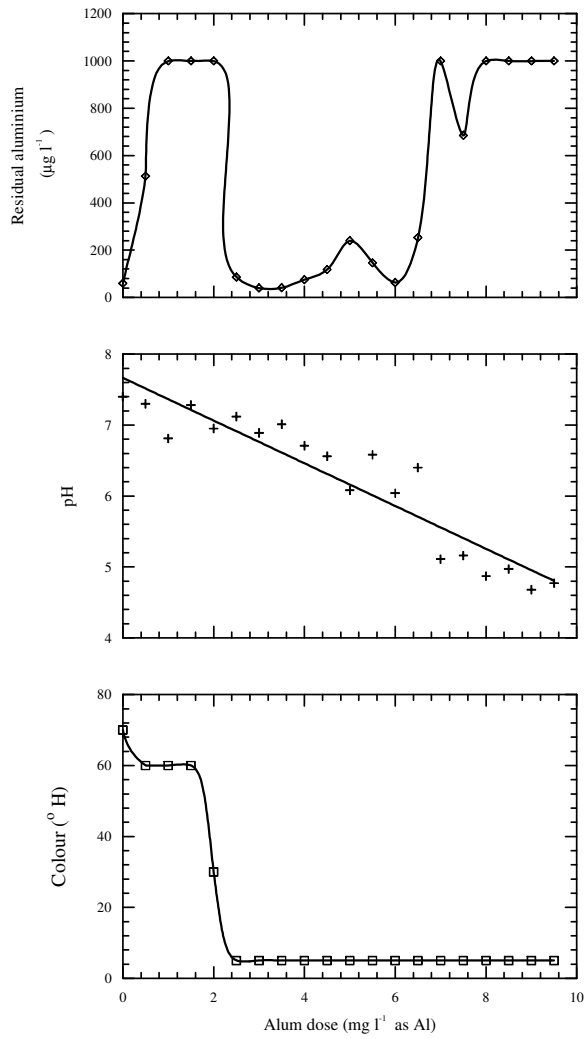


Fig 3.4 Typical jar test results using alum as coagulant
(raw water alkalinity 30 mg l⁻¹ as CaCO₃)

$$= (4/3)R^3 \frac{dv}{dz} \quad (3.13)$$

$$= (1/6)(D_i + D_j)^3 \frac{dv}{dz} \quad (3.14)$$

where D_i and D_j are the diameters of particles i and j , respectively. If there are n_i particles of diameter i per unit volume, then the number of collisions N_j per unit time will be

$$N_j = (1/6)n_i(D_i + D_j)^3 \frac{dv}{dz} \quad (3.15)$$

If n_j is the number of particles of diameter j per unit volume, then the number of collisions per unit volume per unit time will be

$$N_{ij} = (1/6)n_i n_j (D_i + D_j)^3 \frac{dv}{dz} \quad (3.16)$$

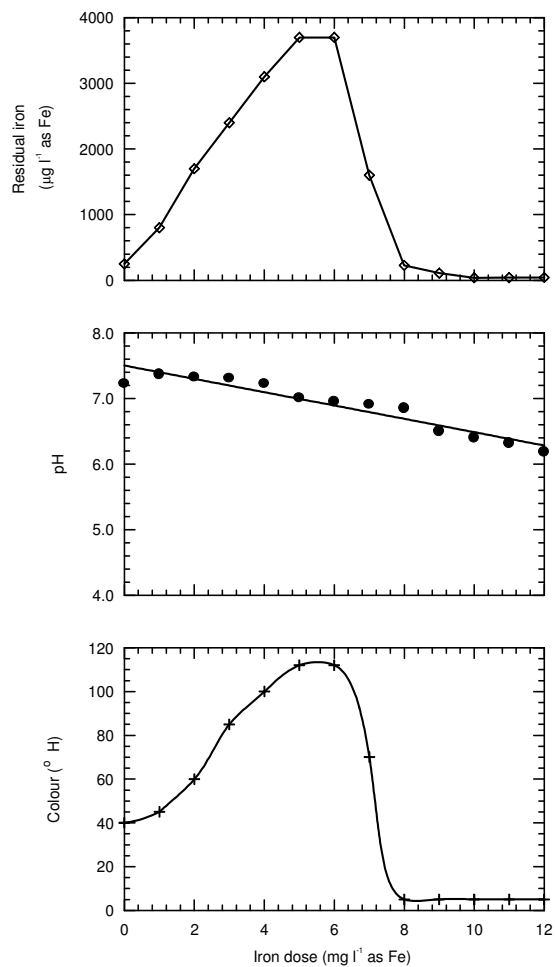


Fig 3.5 Typical jar test results using ferric sulphate (raw water alkalinity 30 mg l⁻¹ as CaCO₃)

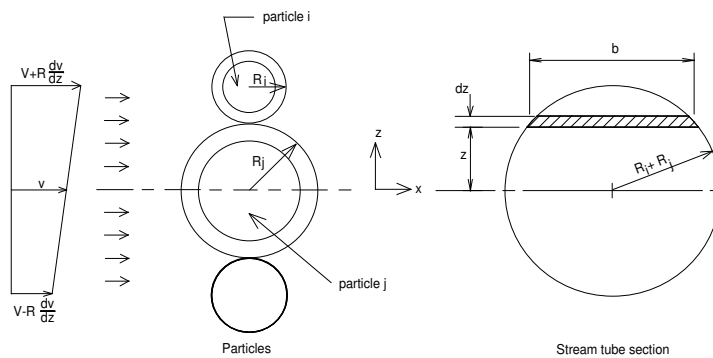


Fig 3.6 Orthokinetic flocculation

The continued existence of velocity gradients in a fluid body requires a power input to the fluid. Consider a small cubical element with a flow in the x-direction and a velocity gradient in the z-direction, as shown in Fig 3.7. In conditions of laminar flow the shear stress is linearly related to the velocity gradient:

$$\text{shear stress } \tau = \mu \frac{dv}{dz} \quad (3.17)$$

$$\text{shear force } F = \tau(\Delta x \cdot \Delta y) = \mu \frac{dv}{dz} (\Delta x \cdot \Delta y) \quad (3.18)$$

$$\text{power } P = F \cdot \frac{dv}{dz} = \mu \left(\frac{dv}{dz} \right)^2 (\Delta x \cdot \Delta y \cdot \Delta z) \quad (3.19)$$

$$\text{power / volume} = P / V = \mu \left(\frac{dv}{dz} \right)^2 = \mu G^2 \quad (3.20)$$

where $G = \frac{dv}{dz}$, the velocity gradient.

$$G = \left(\frac{P}{\mu V} \right)^{0.5} \quad (3.21)$$

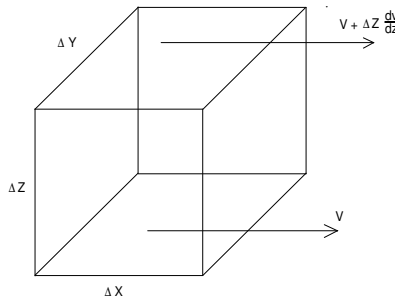


Fig 3.7 Fluid shear strain rate

The extent of particle aggregation is given by the product of the collision rate and flocculation time, i.e. it is proportional to the product Gt, where t is the flocculation time. Experience suggests that operating Gt values should lie within the range 10^4 - 10^5 . Excessive velocity gradients tend to shear floc particles and must therefore be avoided. The operating range suggested for G is 30 - 60 s^{-1} .

3.5.2 Mixing techniques and floc growth

Coagulants are normally added to a water or wastewater flow in the form of concentrated solutions. To ensure uniform dispersion of the coagulant a rapid mixing system is required. Following this initial rapid mix a more gentle agitation is required to establish velocity gradients of a magnitude suitable for flocculation. Either a gravitational or mechanical mixing system may be used.

Gravitational systems have the advantages of simplicity and ease of maintenance. Rapid mixing can be achieved by injection into a turbulent pipe flow (velocity $> 1 \text{ m s}^{-1}$) or at a hydraulic jump in an open channel.

Horizontal-flow basins with fixed baffles or upward flow sludge blanket clarifiers may be used to provide the gentle level of mixing required to promote flocculation. Sludge blanket clarifiers, which combine flocculation and floc separation, are described in Chapter 4. They are commonly used in the production of drinking water.

In a horizontal flow baffled basin of volume $V(\text{m}^3)$, with a flow-through rate $Q (\text{m}^3 \text{s}^{-1})$ and head loss h (m), the power per unit volume is

$$P/V = \rho ghQ/V \quad (3.22)$$

$$= \rho gh/t \quad (3.23)$$

where t is the detention time (s). The velocity gradient is

$$G = (\rho gh/\mu t)^{0.5} \quad (3.24)$$

and

$$Gt = (\rho ght/\mu)^{0.5} \quad (3.25)$$

Baffled basins have the advantage that energy dissipation is not uniformly distributed, being excessive at bends and inadequate in the straights. They are also inflexible in operation.

Upward flow sludge blanket clarifiers may be of the hopper-bottom type (Fig 4.10) or the flat-bottom type (Fig 4.11). The sludge blanket is maintained in a fluidised state by the upward flow water. The total quantity of sludge in the blanket is kept constant by bleeding off sludge from the top of the blanket at a rate equal to the sludge inflow rate. Velocity gradients are created within the blanket by the shear drag which the blanket exerts on the upward fluid flow. With a stationary blanket, the hindered settling velocity of floc particles at any level must equal the upward bulk flow velocity at that level:

$$v_h = \frac{Q}{A} \quad (3.26)$$

$$v_h = v_t (1 - Kc^{2/3}) \quad (3.27)$$

and hence

$$c = \left[\left(1 - \frac{Q}{Av_t} \right) \frac{1}{K} \right]^{3/2} \quad (3.28)$$

According to equation (3.28), c increases with A . A is constant in flat-bottom tanks, hence c should also be constant over the blanket depth in such tanks. In hopper-bottom tanks c should have a maximum value at the top of the blanket. The magnitude of the velocity gradients created within the blanket can be obtained by equating the drag force on the suspension to its submerged weight:

drag force/unit volume = $c(\rho_s - \rho)g$ = pressure drop per unit length, and

$$\begin{aligned} \text{power/unit volume} &= c(\rho_s - \rho)g \frac{Q}{A} \\ &= \mu G^2 \end{aligned} \quad (3.29)$$

and hence

$$G = \left[\frac{c}{\mu} (\rho_s - \rho)g \frac{Q}{A} \right]^{0.5} \quad (3.30)$$

The value of G is thus theoretically constant in a flat-bottom clarifier. In a hopper-bottom tank, c and A vary with depth. Computations, based on equations (3.27) and (3.30), show (Ives, 1968) that the value of G decreases from the bottom of the blanket to the top in a hopper-bottom tank.

The detention time in the sludge blanket is given by the relation

$$t = V_b(1-c)/Q \quad (3.31)$$

where V_b is the sludge blanket volume. The flocculation criterion, Gt , may be calculated as being the product of the mean values of G and t .

Ives (1968) has suggested that the product Gct might be a more significant flocculation criterion than Gt for sludge blanket clarifiers owing to the obvious influence of c on collision opportunity. He did not, however, suggest an optimum value for Gct .

Mechanical mixing systems may be of the high speed propeller types for rapid mixing of the slow-speed paddle type for flocculation. The power input of the latter may be calculated as follows:

$$P = \frac{C_d A \rho v_r^2 v}{2} \quad (3.32)$$

where C_d is the drag coefficient for the blades, A is the blade area, v is the mean blade velocity and v_r is the velocity of the blade relative to the fluid. Since

$$P/V = \mu G^2$$

Then

$$G = \left[\frac{C_d A \rho v_r^2 v}{2V\mu} \right]^{0.5} \quad (3.33)$$

In flocculation practice (Cox, 1964) peripheral speeds of paddles vary within the range $0.2-0.6 \text{ m s}^{-1}$; the relative blade velocity in the absence of fixed baffles is about 0.75 times the peripheral velocity, and the drag coefficient C_d for flat blades is about 1.8; the paddle blade area is usually between 15% and 25% of the tank cross-section area and the detention time is typically 20-40 minutes.

3.5.4 Influence of temperature on coagulation

As with virtually all other water and wastewater treatment processes, temperature has a significant influence on coagulation kinetics. A drop in temperature causes: (a) a reduction in the rate of chemical reaction of added coagulants; (b) an increase in water viscosity and hence a reduction in the mean velocity gradient for a given power input and hence also a reduction in mean particle settling velocity; and (c) a reduction in colloid activity. The combined effects of these factors leads to a reduction in process effectiveness with falling temperature.

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