Chapter II

LITERATURE AND THEORETICAL REVIEW

The study of criteria of sludge blanket clarifier encompasses many areas. Among these are the theory of coagulation, the chemical reaction of the coagulant used, the flocculation, settling of particles, the sludge concentration, upflow velocity and sludge blowoff.

2.1 Theory of Coagulation

Coagulation is defined as the results of electrical and chemical action brought about in water following the addition of coagulating chemicals. There are many variables involved in the coagulation treatment of a raw water. They include chemical factors, such as the nature of suspended and colloidal solids, the nature and concentration of coagulants and water and the velocity gradients.

The flocculating effect of small amounts of salt on a colloidal dispersion is one of the basic phenomena of colloid chemistry. From the sticking together of the particles upon collision, it is obvious that attractive forces must be existing between the particles. The attractive force between dispersed particles is distributed to the van der Waal's attractive forces between all the atoms of one particle and all the atoms of the others. The magnitude of this total force depends on the size and shape of the particles and, to some extent, on the character of the dispersion medium.

It has been found by investigators that colloidal particles in natural waters are normally negatively charged and that the positive aluminium or ferric ion can neutralize this charge, thereby removing the forces of mutual repulsion existing between the particles of impurity. Hence, the van der Waal's force becomes effective resulting in the coagulation of the colloidal particles.

2.2 Effect of Impurities on Coagulation

2.2.1 Effect of Turbidity

In a very low turbidity water, there is not enough particulate matter to form a large floc in reasonable time. More highly turbid waters can be coagulated very quickly and filtered to give a clear effluent.

PACKHAM (1963) discovered that the dose of aluminium sulfate required for coagulation is largely independent of the nature of the material in suspension. The samples of suspended solids isolated from rivers behaved largely in the same way as the pure minerals in equal concentrations and were apparently unaffected by the present of large quantities of organic matter.

2.2.2 Effect of pH

The optimum pH for removal of negative colloids varies somewhat with the nature of the water but usually falls in the range of pH 5.0 to 6.5 and 7 to 9.0. All desirable products of reaction could only be formed at a particular pH range and an optimum coagulant dose. The solubility of $Al(OH)_3$ is pH dependent and is low between pH 5 and 7.5, outside this range coagulation with aluminium salts is not successful (HUDSON 1965).

2.2.3 Effect of Alkalinity

The alum used in water treatment is filter alum, $Al_2(SO_4)_3 \cdot 14H_2O$, and alkalinity present in natural waters is predominantly $Ca(HCO_3)_2$. The reaction of alum in water can be written as:

$$Al_2(SO_4)_3 \cdot 14H_2O + 3Ca(HCO_3)_2 = 2Al(OH)_3 + 3CaSO_4 + 6CO_2 + 14H_2O \quad \ldots\ldots\ldots\ldots \quad (1)$$

It is found that 1 mg/l alum destroys 0.5 mg/l alkalinity as $CaCO_3$. Thus for satisfactory coagulation sufficient alkalinity must be available to react with the alum and also to leave a suitable residual in the treated water.

2.2.4 Effect of Temperature

The coagulated water going to the filters is usually less well prepared for the filters in winter than in summer. The settled effluent from the clarifiers contains more and finer floc in winter, and more coagulant is usually required to produce a satisfactory filter effluent (CAMP 1940). These difficulties are usually ascribed to the effect of the temperature on coagulation. The upflow velocity of clarifiers will decrease at low temperatures, it can be explained as a consequence of higher water viscosity (TESARIK 1967).

2.3 Zeta Potential

Turbidity is electronegative and must be regarded as consisting of two distinct and separate fractions: (1) a coarse fraction with particle diameter of 1 mm - 1 µ and (2) a fine (colloidal) fraction with particle diameter of 1 µ - 10 Å (RIDDICK 1961).

The coarse fraction may be successfully removed from raw waters by conventional alum coagulation, but the fine fraction cannot. Its colloidal size prevents sedimentation, and its electronegative zeta potential (ZP in the range of 15-25 mv) prevents agglomeration (RIDDICK 1961). As conventional alum floc is also electronegative in about this same millivoltage range, a mutual repulsion exists between the floc particles and the colloids, and these repelling forces prevent the colloid from making permanent contact with the floc, regardless of agitation, raw water colloids can be effectively removed by lowering the zeta potential of both the floc and the colloid to a value of approximately zero plus or minus about 5 mv. This can be done by simultaneously employing the proper dosage of an inorganic coagulant and an appropriate organic polyelectrolyte. BLACK & HANNAH stated (1961): "the best removal of turbidity occurs where the zeta potential has been neutralized".

As ZP measurements indicate clearly the accuracy of control of chemical treatment on a plant scale, they present an immediate opportunity for better operating cost control. Chemical, particularly alum, losses from the use of an excess may be controlled by routine ZP measurement on the treated water.

2.4 Theory of Flocculation

The precipitates first formed by the chemical reactions are crystals of molecular size. The initial increase in size of these colloidal crystals is caused by true diffusion or Brownian motion. The completion of the coagulation process requires gentle turbulent mixing of the suspension.

In 1943 Camp and Stein stated that the rate of flocculation caused by the motion of the fluid (at a point in a fluid) is directly proportional to the absolute velocity gradient or space rate of change of velocity at that point and is directly proportional to the concentration of flocculable particles at that point.

The velocity gradients at any instant throughout a vessel or chamber in use for flocculation vary considerably in magnitude, being greatest at the solid boundaries of the paddles or other devices used to introduce the mixing motion and being least in the corners of the chamber farthest from the point of introduction of the motion.

The rate of power dissipation (the work of shear per unit of volume per unit of time at a point) is known as the dissipation function. The mean value of the dissipation function, designated as P, is equal to the total power dissipation divided by the volume of the chamber or conduit. The root mean-square velocity gradient is defined by the following relationship.

$$G = \sqrt{\frac{P}{\mu}} \quad .... \quad (2)$$

In which G is the root-mean square velocity gradient in the chamber and μ is the absolute viscosity of the fluid. For mechanical mixers, operated by paddles, the useful power input is a function of the drag of the paddles. If D is the drag in lb, C_D is the coefficient of drag for plates moved face-on to the fluid, A is the area of the paddle in sq ft., v is the velocity of the paddles relative to that of the liquid in fps, and V is the volume of the flocculator in cu. ft., the drag is

$$D = C_D A w v^2/2g = C_D A \rho v^2/2 \qquad \text{..........} \quad (3)$$

and the power per unit volume of water, P, which equals force times velocity divided by volume, becomes

$$P = C_D A \rho v^3/(2V) = \mu G^2 \qquad \text{..........} \quad (4)$$

$$G = \sqrt{C_D A v^3/(2 \nu V)} \qquad \text{..........} \quad (5)$$

In practice peripheral speeds of paddles range from 3 fps to 0.3 fps FAIR & GEYER stated that the value of G should be greater than 10 fps/ft in order to promote flocculation but less than 75 fps per ft. Optimum values appears to lie between 30 and 60 fps per ft (FAIR & GEYER 1954).

As long ago as 1917, Von Smoluchowski showed that orthokinetic flocculation in a uniform velocity gradient is characterized by the equation

$$\frac{dN}{dt} = \frac{G}{6} n_1 n_2 (d_1 + d_2)^3 \qquad \text{..........} \quad (6)$$

When $\frac{dN}{dt}$ is the rate of collision of 1- particles and 2- particles per unit volume of water,

G is the velocity gradient,

n_1, n_2 are the number of 1- and 2- particles respectively per unit volume of water,

d_1, d_2 are the diameters of the 1- and 2- particles respectively.

Studies by Robeck and Riddick indicate the n_1 is in the order of 10 particles per milliliter, and nearly all particles causing turbidity are smaller than 10 μ in diameter, with the majority smaller than 1.5 μ. In contrast to these figures, floc particles are often 100-2,000 μ and their number in flocculating water is only a small fraction of n_1 (HUDSON 1965). The effect of d_1 on Eq.6 is therefore small and the term may be omitted with little error,

$$\frac{dN}{dt} = -\frac{dn_1}{dt}$$

because it will be the disappearance of the primary particles and natural particles which will be noted, and

$$n_2 = \text{constant}$$

because a floc blanket should be in equilibrium with floc withdrawn at a rate equal to its creation from addition of coagulant (IVES 1968). Consequently equation (6) becomes

$$-\frac{dn_1}{dt} = \frac{G}{6} n_1 \, n_2 \, d_2^3 \qquad \text{..........} \quad (7)$$

For $\frac{\pi n_2}{6} d_2^3$ = volume of floc particles per unit volume of blanket

= C

Where C is the floc volume concentration

$$-\frac{dn_1}{dt} = \frac{G n_1 C}{\pi} \qquad \text{..........} \quad (8)$$

Integrating Eq. (8) we get

$$\frac{n_t}{n_o} = \exp.\left(-\frac{GCt}{\pi}\right) \qquad \text{..........} \quad (9)$$

Where n_o = the number of primary particles per unit volume of the water before orthokinetic flocculation,

n_t = the number of primary particles remaining per unit volume of the water after time t.

Thus the process of flocculation in a sludge blanket is characterized by the dimensionless group GCt. The dimensionless product Gt used in text book (FAIR & GEYER) was found inadequate in predicting the course of flocculation. It is from Eq.(9) that the product GtC correctly represents the flocculation kinetics rather than the product Gt. (IVES 1968).

2.5 Theory of Settling

2.5.1 Settling Velocities of Individual Particles

When a particle is released in a still fluid it will move vertically due to gravity if its density is differs from that of the fluid. The particle accelerate until the frictional drag of the fluid approaches the value of the impelling force, after which the vertical velocity of the particle with respect to the fluid at rest will be **sub**stantially constant. The terminal velocity is known as the settling velocity of the particle.

The general equation for the settling velocity of spheres of diameter D in terms of the drag coefficient may be obtained by equating the impelling force to the drag.

$$v = \sqrt{\frac{4}{3}\frac{g}{C_D}\frac{\rho_1-\rho}{\rho}D} \qquad \text{..........} \quad (10)$$

Particles to be removed from water by sedimentation are seldom truly spherical and are usually quite irregular in shape. In water treated by coagulants, the suspended particles consist of precipitated Al_2O_3 floc with its adsorbed water and the enmeshed solids of the raw water. The floc particles may contain entrained water up to about 99% of the volume, with a corresponding reduction in density to about 1.002. The density of the floc particles is further modified by the amount and character of solids entrapped from the raw water (CAMP 1946).

2.5.2 Settling of Rigid Particles

If a suspension of discrete particles is allowed to settle in a still water, it will be observed that the top of the suspension falls at a uniform rate until all the particles are deposited on the bottom of the container. If the particles are rigid, they will pack on the bottom as closely as their shape will permit, and then compact no further.

2.5.3 Hindered Settling

As a particle falls, it continually displaces the liquid below it. The displace liquid flows upwards and around it giving drag resistance. If the particles are widely separated, the concentration is low, a particle will not be affected by its neighbours, but will fall at the same rate as an isolated individual particle. As the concentration increases, the particles will restrict the area through which the displaced liquid flows up; the velocity of this liquid will increase, and the particles will settle at lower velocity. This phenomenon is known as hindered settling.

2.6 Hydrodynamic Principles of Sludge Blanket Clarifier

In a fluidised bed a high concentration of solid particles is held in suspension by upward flow of a liquid. The basic principle of fluidised bed formation could be seen as a hindered sedimentation effect. The sedimentation velocity of a single particle is greater than the sedimentation velocity of the same particle in the presence of a large concentration of other particles. When the upward flow of liquid does not exceed the sedimentation velocity of the fluidised bed, a well-defined boundary surface is formed between the particles in suspension and the liquid leaving at the top of the fluidised bed.

The upward flow itself would not be sufficient to maintain the bed of suspended particles in fully fluidised conditions. To prevent sedimentation, a zone of high turbulence at the inlet to the fluidisation vessel ensures that suspended particles reach the fluidised bed. The high energy of the incoming water is reduced in the fluidised bed by the turbulent dissipation of energy and because of the great concentration of suspension is in the upper layers of the bed height, the flow through the fluidised bed could be compared with percolation through a granular porous medium. The flow in such a medium is uniformly distributed, turbulence highly reduced, and for certain conditions laminar flow may even prevail. The reduction of inlet energy could be increased by suitable conical shape of the fluidisation vessel, by diminishing the mean velocity of flow. The reduction of turbulence in the fluidised bed and uniform distribution of flow at the top of the bed is an important condition for the formation of a stable surface of the fluidised bed. The water leaving under such conditions at the top of the sludge blanket has too low a velocity to support an isolated solid particle in suspension and any particle escaping the fluidised bed would, under these conditions, readily return into the bed.

When the liquid entering the fluidised bed contains suspended particles comparable with the size of particles constituting the fluidised bed, they are retained in this medium. By retaining these particles the fluidised bed tends to grow. The densities of the fluidised bed and the liquid separated from the particles leaving the top of fluidised bed are different. This provides favourable conditions for continuous separation of the incoming suspension from the liquid. Introduction of a submerged overflow weir at the top of the fluidised bed will fix the top of the fluidised bed at the level of the weir. When the volume of fluidised bed is increased, due to the retention of the incoming solid particles, the excess of suspension will overflow the weir and thence descend under gravity, due to the higher density of these particles than the liquid. On this simple hydrodynamic principle is based the separation process known in water treatment and purification technology as "sludge blanket clarification.

The specific feature of a fluidised bed in a sludge blanket clarifier is the fact that the suspension particles constituting the sludge blanket are not discrete uni-sized particles, but floc suspension subject to aggregation. Such floc particles formed by coagulation could be further aggregated into large particles or broken down. The mode of this action depends on the growth properties of the flocs, their resistance to shear forces, and on turbulent velocity spectra in the sludge blanket zone of the clarifier. Because of the flocculation ability of the floc particles in the sludge blanket, flocs can be retained which do not necessarily conform to the mean size of the sludge blanket particles. The incoming flocs are usually in the stage of so-called "microflocs", which are on the boundary of colloidal and suspension stages, but suitable for further aggregation. This size of floc suspension would be completely inadequate for separation by sedimentation; however, for separation in a sludge blanket it is entirely sufficient. Therefore the coagulation process can usually be confined only to the time needed for conversion from the colloidal stage to the suspended state, and no flocculation process is required to produce large, well-settling flocs. Even when such large flocs are produced, they are broken down at the inlet to the sludge blanket due to the shear forces created by great turbulence prevailing in this region. As turbulence of the flow diminishes with the distance from the inlet, the breaking of the flocs is reduced and at some point breaking action is changed into aggregation. This aggregation is due to the contact between the suspended particles brought about by turbulent velocity gradients.

From this point of view, the theoretical upflow separation velocity in the sludge blanket would be only a function of floc characteristics and their size distribution. This theoretical separation velocity would be relatively high, and for properly flocculated floc suspension would represent much higher upflow velocity than can be obtained in practice.

2.7 The Nature of Sludge Blanket Instability

The basic limitation in the sludge blanket separation efficiency lies principally in the instability conditions of the fluidised bed. Because of the higher density of the fluidised bed, this tends to settle down due to gravity forces. Only the upward flow and high turbulence at the inlet maintain the bed in fluidised condition.

The most detrimental instability phenomenon affecting sludge blanket performance is the formation of currents in the sludge blanket, disturbing the uniform distribution of flow. Such currents due to the hydrodynamic instability conditions are always present in fluidised beds and cannot be entirely removed.

Instability currents can originate from any kind of disturbance, as for example by non-uniform floc size distribution. The floc particles in the upper part of the sludge blanket can flocculate to such dimensions that they may not be maintained in suspension by upward flow and start to settle. By this action a descending current is formed and promotes an instability current which is duly transferred to the bottom of the fully fluidised bed where the turbulence is sufficiently pronounced to break the descending large floc particles. The broken flocs are then taken by the upward flow to the top of the sludge blanket, where they again flocculate into large ones. However, any such downward stream inevitably causes a consequent upward flow in another part of the clarifier. When such an upward flow reaches the top, it causes eruptions on the surface of the sludge blanket.

Due to the uniform distribution of flow and low turbulence region at the top of the sludge blanket, the separation conditions are best in the immediate vicinity of the surface of the blanket. At greater distance from the surface, turbulence increases and uniformity of flow is reduced by density currents in the clear water zone. Eruptions caused by upward instability currents disturb the separation surface of the sludge blanket, and by this action the flocs are thrown far into the clear water zone maintained by upflow streams and carried to the collecting weirs. When the stability of the blanket is sufficiently high, the stable surface could be maintained even for a relatively high upflow velocity. Therefore the main objective of the sludge blanket clarifier design is in obtaining the most stable conditions of the sludge blanket for high separation efficiency at maximum upflow rate.

2.8 Stability Condition of the Sludge Blanket

From the hydrodynamic principles of the sludge blanket clarifiers, the stability conditions turn out to be the determining factors for the separation efficiency and rate of flow of such devices. The degree of stability of a sludge blanket depends on following factors:-

2.8.1 The inlet conditions

To maintain the sludge blanket in a fully fluidised state, high velocity and turbulence at the inlet to the sludge blanket are required. The sludge blanket performance is **always very** sensitive to the magnitude of velocity of the incoming water. A velocity greater than that required would provide excess energy in the incoming water. This energy is reduced only through turbulent dissipation in the sludge blanket. Excess energy largely increases the instability conditions of the sludge blanket. On the other hand, a lower inlet velocity than optimum would be insufficient to prevent sedimentation. Even small deviations from the optimal inlet velocity have a great detrimental effect on the sludge blanket performance.

Any irregularity in the distribution of the water entering the sludge blanket zone may also cause a great deterioration of the clarifier performance. Only the relatively high inlet velocity could explain the enormous dependence of sludge blanket stability on the inlet conditions. Due to the high velocity, any irregularity in incoming flow is readily propagated through the whole sludge blanket, enlarging instability currents always present in the blanket. Excess energy at the entrance helps propagate these perturbations. Therefore in any clarifier design the inlet conditions are of most importance.

The inlet conditions proved to be so decisive for the effectiveness of operation that the different designs of sludge blanket clarifier (based on the fully fluidised bed principle) could be classified with respect to the distribution system used. Up to now, four different inlet distribution systems into the sludge blanket are known.

2.8.1.1 Perforated plate distribution system - High inlet velocity with appropriate turbulence at the bottom of the clarifier can be obtained by using a perforated plate for distribution of the incoming water into the sludge blanket zone. However, the uniform distribution obtained by this system proved to be unsatisfactory, due to the clogging of the space beneath the plate. Such clogging disturbed the uniform distribution of flow and after a long period of operation the clarifier became clogged. Because of many disadvantages, the perforated plate system was abandoned.

2.8.1.2 Point inlet distribution system - The single point inlet distribution system usually comprises a conical vessel with a pipe inlet at the bottom. In this system the inlet velocity is unnecessarily high and excess incoming water energy is dissipated in the sludge blanket tends to be unstable. For less favourable conditions, separate coagulators are required to provide sufficient detention time for completion of coagulation reactions. The excessively high inlet velocity could be reduced by using a multiple point inlet system consisting of many point inlets. However, too many inlets present difficulties in providing uniform distribution of water into each of them.

2.8.1.3 Perforated pipes distribution system - This system is equivalent to a multiple point inlet system with a very large number of inlet orifices. Using this system, the energy of incoming water is reduced substantially and the stability of the sludge blanket increased. However, to obtain optimal inlet velocity, a large number of pipes should be used. To maintain uniform flow distribution in such a large pipe system is difficult, because of clogging of orifices and pipes by flocs. Therefore, for accomplishing a uniform distribution and for preventing clogging, pulsation can be used.

2.8.1.4 Slot distribution system - In this system a uniform distribution of coagulated water into the conical sludge blanket zone is provided by a narrow slot inlet. For large clarifiers more than one slot inlet can be used. The dimensions of the inlet slot can be easily designed to obtain the optimal inlet velocity. The adaptability of the size of the inlet slot is one of the greatest advantages of this system compared with the previous ones.

2.8.2 Removal of excess of the suspension from the sludge blanket and sludge concentration

Excess floc suspension in a fully fluidised sludge blanket is continuously removed from the top of the blanket. The removal of floc suspension is usually accomplished by a submerged **weir**, over which the excess flocs overflow into the sludge concentrator. The separation of the flocs from water in the sludge concentrator is brought about by sedimentation. In the sludge concentrator, density currents may easily be formed by differences of temperature or of floc concentration. Such currents, emerging from the concentrator and reaching the blanket zone, would have a large effect on the separation efficiency of the clarifier. This unfavourable effect could be avoided by introducing controlled flow of a small percentage of treated water into the sludge concentrator. Such a forced controlled flow not only prevents the density current reaching the sludge blanket zone, but largely reduces the possibility of density current formation, so providing a more homogenous sedimentation condition for separation of suspension in an upward flow.

2.8.3 Clear water collecting system

Water leaving the sludge blanket has insufficient vertical velocity to support the flocs in suspension, thus providing very favourable separation conditions. This is due principally to the presence of a high concentration of floc suspension at the top of the blanket, which represents some sort of porous medium. For this reason, the separation process in the sludge blanket is sometimes compared with a filtration process. A badly designed collecting system could interfere with the uniform distribution of flow in the zone, and thus increase the uptake of floc from the blanket, causing a greater load on the filters. The flow conditions in the clear water zone depend on the depth of this zone, on the location of clear-water collecting weirs, on the location of submerged weir for sludge removal and on the rate of flow into the sludge concentrator (MACKRLE 1965).