
14 Coagulation and flocculation

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14 Coagulation and flocculation

14.1 Introduction

Coagulation and flocculation provide the water treatment process by which finely divided suspended and colloidal matter in the water is made to agglomerate and form flocs. This enables their removal by sedimentation, dissolved air flotation or filtration. Colloidal particles (colloids) are midway in size¹ between dissolved solids and suspended matter. Colloids are kept in suspension (stabilised) by electrostatic repulsion and hydration. Electrostatic repulsion occurs because colloids usually have a surface charge due to the presence of a double layer of ions around each particle. Thus, the colloid has an electric charge, mostly a negative one. Hydration is the reaction of particles at their surface with the surrounding water. The resulting particle-water agglomerates have a specific gravity, which differs little from that of water itself.

The substances that frequently are to be removed by coagulation and flocculation are those that cause turbidity and colour. Surface waters in tropical countries often are turbid and contain colouring material. Turbidity may result from soil erosion, algal growth or animal/vegetable debris carried by surface run-off. Substances leached from decomposed organic matter, leaves, or soil such as peat may impart colour. Both turbidity and colour are mostly present as colloidal particles.

The electrostatic repulsion between colloidal particles effectively cancels out the electronic attraction forces (Van der Waals' forces) that would attach the particles together. Certain chemicals (called coagulating agents, coagulants) have the capacity to compress the double layer of ions around the colloidal particles. They reduce the range of the electrostatic repulsion, and thus enable the particles to flocculate, i.e. to form flocs. These flocs can grow to a sufficient size and specific weight to allow their removal by settling, flotation or filtration.

Generally water treatment processes involving the use of chemicals are not so suitable for small community water supplies. They should be avoided whenever possible. Chemical coagulation and flocculation should only be used when the needed treatment result cannot be achieved with another treatment process using no chemicals. If the turbidity and colour of the raw water are not much higher than is permissible for drinking water, it should be possible to avoid chemical coagulation in the treatment of the water. A process such as slow sand filtration or multi-stage filtration would serve both to reduce the turbidity and colour to acceptable levels, and to improve the other water quality characteristics, in a single unit. A roughing filter can serve to reduce the turbidity load on the slow sand filter, if necessary.

1 Size range: 5×10^{-3} – $2 \cdot 10^{-1}$ micrometer (0.2 microns)

14.2 Coagulants

Alum ($\text{Al}_2(\text{SO}_4)_3 \cdot n\text{H}_2\text{O}$) where $n=14, 16, \text{ or } 18$, depends on the form of alum supplied. This may be in liquid solution, broken crystalline granules 2-5 cm size (kibbled) or crystalline blocks. It is by far the most widely used coagulant. Iron salts (e.g. ferric chloride (FeCl_3), or ferric sulphate ($\text{Fe}_2(\text{SO}_4)_3 \cdot 9\text{H}_2\text{O}$)) can be used as well and in some instances have advantages over alum. A significant advantage of iron salts over aluminium is the broader pH² range for good coagulation. Thus, in the treatment of soft coloured waters where colour removal is best obtained at low pHs, iron salts may be preferred as coagulants. Iron salts should also be considered for coagulation at high pHs, since ferric hydroxide is highly insoluble in contrast to aluminium salts, which form soluble aluminate ions at high pHs. Sodium aluminate is mostly used for coagulation at medium pHs. Synthetic organic polyelectrolytes have become available as coagulants but are generally not economical for small water supply systems, nor are they readily available.

The use of extracts from the crushed seeds of certain tropical trees is described in detail in the next section, 14.3.

Coagulants such as soluble aluminium and iron salts react with the alkalinity of the water, and hydrolyse in it. For example, alum reacts to form aluminium-hydroxide floc, $\text{Al}(\text{OH})_3$, a gelatinous precipitate. The required alkalinity may be naturally present in the water or it has to be added through dosage of lime, $\text{Ca}(\text{OH})_2$ or sodium carbonate, Na_2CO_3 (also called soda ash).

For good coagulation the optimal dose of coagulant should be fed into the water and quickly and properly mixed with it. The optimal dose will vary depending upon the nature of the raw water and its overall composition. It is not possible to compute the optimal coagulant dose for a particular raw water. A laboratory experiment called the *jar test* is generally used for the periodic determination of the optimal dose.

The jar test may be briefly described as follows:

A series of samples of water are placed on a special multiple stirrer and the samples, typically 800 ml in 1-litre beakers (or jars), are dosed with a range of coagulant, e.g. 10, 20, 30, 40 and 50 mg/l, and are stirred vigorously for about one minute. Then follows a gentle stirring (10 minutes), after which the samples are allowed to stand and settle for 30-60 minutes. The samples are then examined for colour and turbidity and the lowest dose of coagulant that gives satisfactory clarification of the water is noted.

2 Measure of the acidity/alkalinity of water. Acid water has a pH below 7, the pH of alkaline water is higher than 7.

A second test involves the preparation of samples with the pH adjusted so that the samples cover a range (e.g. pH = 5, 6, 7 and 8). The coagulant dose determined previously is added to each beaker. Then follows stirring, flocculation and settlement as before. After this, the samples are examined and the optimum pH is determined. If necessary, a re-check of the minimum coagulant dose can be done.

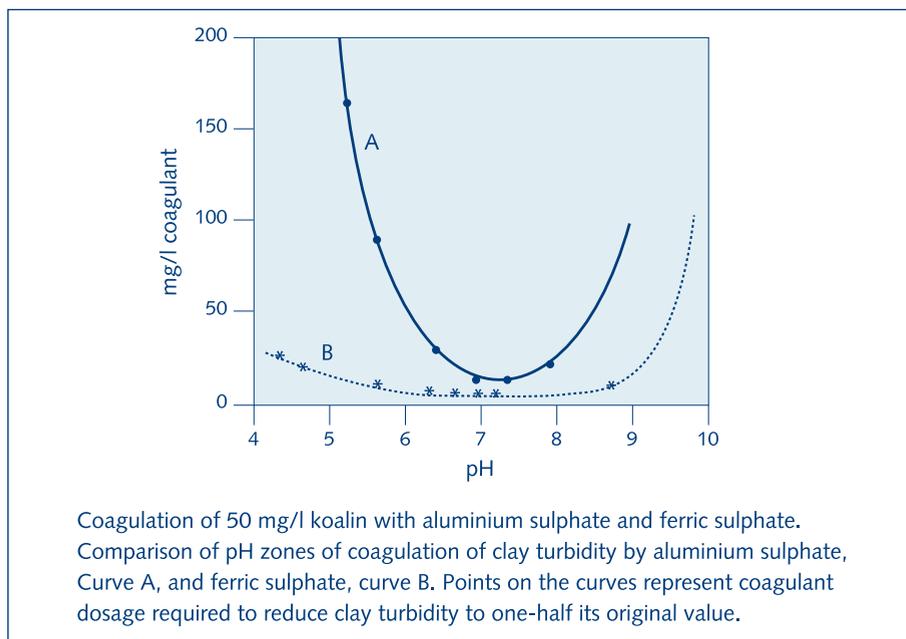


Fig. 14.1. pH zone-coagulation relationship (Adapted from R.F. Packham)

As mentioned earlier, aluminium and iron salts have considerable differences in their pH zones of good coagulation. For alum the pH zone for optimum coagulation is quite narrow, ranging from about 6.5-7.5. The comparable range for ferric sulphate is considerably broader, a pH range of about 5.5-9.0 (Fig. 14.1). When the results of a jar test are plotted, this type of curve is typical.

The most common method of dosing the alum or ferric sulphate is in the form of a solution. Such a solution (usually of 3-7% strength, that is, 30-70 kg alum $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$ per m^3 water) is prepared in special tanks with a holding capacity of ten or more hours coagulant feeding requirements. Two tanks are required, one in operation, while the solution is being prepared in the other.

When using alum, one should keep in mind that in solutions of less than 1% strength, the chemical is hydrolysed (i.e. forms agglomerates with the chemical feed water) before it is dosed into the raw water. To prevent this, the solution should always have a strength of more than 1.5%.

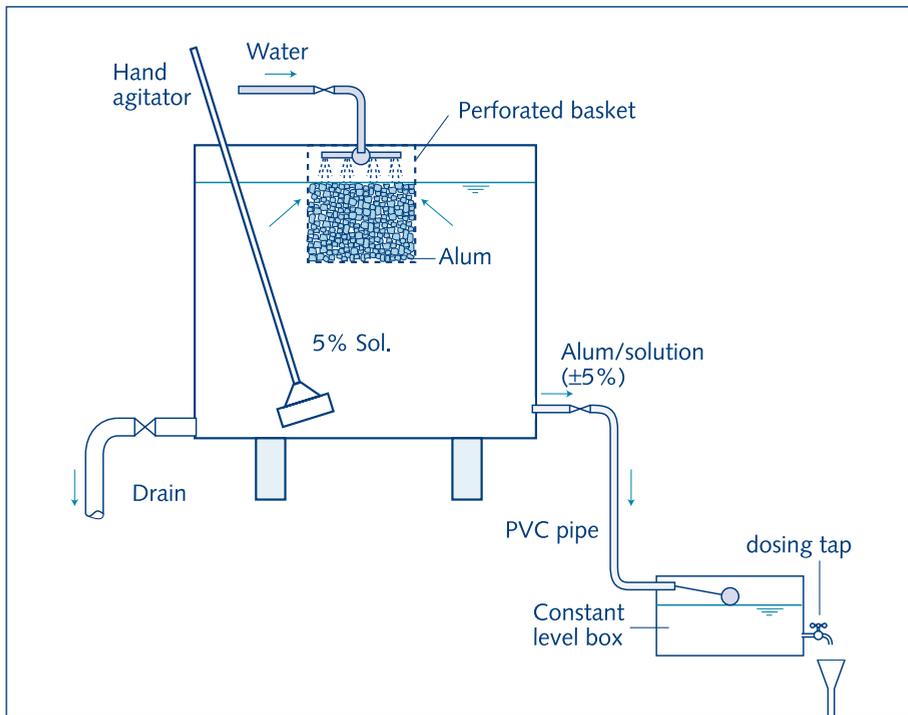


Fig. 14.2. Chemical feed arrangement for alum

Various chemical feed arrangements can be used. Figure 14.2 shows an example.

The simplest method of using lime is in the form of a suspension led into a special tank (called a *lime saturator*), to produce a saturated solution of calcium hydroxide. The size of the tank depends on the required lime dosage.

14.3 Coagulation and flocculation with extracts of particular seeds

Special contribution from Dr. Samia Al Azharia Jahn, Water Treatment Adviser

Botanical identification

Early attempts at water coagulation with plant materials arose through “self-help” by poor people who had no access to groundwater. In India the seeds of *Strychnos potatorum* (table 14.1) have been used to clarify turbid water since the first centuries AD. Where this wild tree was not available, kernels of *Prunus* species and seeds of legumes (*Papilionoidea*) became substitutes. In the Northern Sudan, seeds of *Moringa oleifera* were tried out instead of beans and groundnuts. A relationship between the botanical type and a content of coagulants (chemotaxonomy) could be detected for several plant genera and families.

Table 14.1 Seed extracts that contain outstanding natural coagulants¹

Plant	Chemical nature of coagulant	Raw water, turbidity range, application	Reference
<i>Strychnos potatorum</i> (clearing nut)	mannogalactan, probably anionic polyelectrolyte	Jamuna River (India): ca. 200-2200 NTU, recommended as coagulant aid	Bulusu and Sharma 1965
<i>Moringa oleifera</i> (horseradish tree)	basic polypeptides cationic polyelectrolyte	White Nile (Sudan): 50-250 NTU; Blue Nile: > 30 NTU-several thousand NTU, fast acting primary coagulant	Jahn 1986, 1988
<i>Moringa stenopetala</i>	similar basic polypeptides	performance like <i>Moringa oleifera</i>	Jahn 1986, 1988
five other species of <i>Moringa</i>	not yet known	performance like <i>Moringa oleifera</i>	Jahn 1986, 1988
<i>Vicia faba</i> (broad bean)	not known	Blue Nile: > 800 NTU slow acting primary coagulant	Jahn 1986, 1988
<i>Prunus armeniaca</i> (apricot) ² , and <i>P.amygdalis</i> (almond)	not known	River Nile, Egypt Changjiang, China	Alpino 1591, d'Arcet 1838, Lu Yu 1170
<i>Prunus persica</i> (peach)	not known	Oranje River, Lesotho rivers of Potosí Bolivia	Offringa 1993, Soliz Rodriguez 1984

1 For details and bibliography cf. Jahn 1986, 1988, 1994

2 Apricot kernels were in Egypt, North Sudan and Sichuan (China) still in use in the 20th century

Chemical composition and toxicology

Certain seeds contain substances for the growth of the seedling, which also have flocculating properties. The polyelectrolytes of *Moringa oleifera*, *M. stenopetala* and *Strychnos potatorum* are examples of such flocculating substances (table 14.1). The destabilisation of water colloids is due to positive or negative charges. The cationic electrolytes of *Moringa* are presumed to act like cations of metal coagulants. Alum and a seed extract different impacts on several chemical and physical characteristics of coagulation (table 14.2). *Moringa* seeds contain seed oil and a germicide. The smell and taste effect on the water is very small, even for the maximum *Moringa* seed dose (200-250 mg/l). In the low range of the optimal doses there is no germicide effect and there are no risks from toxic substances. The possible health effects from toxic substances in *Strychnos potatorum* seeds and *Prunus* kernels have not been investigated yet (Jahn, 1988, 1994).

Table 14.2 Differences between water coagulation with alum and *Moringa oleifera* seed extract

Parameters	Aluminium sulphate	Moringa seed extract
Destabilisation	Al ³⁺	cationic polyelectrolytes
Support of aggregation	adsorption at Al(OH) ₃ flocs	none
Efficiency at low turbidity	still satisfactory at 3 NTU	failing below 30 NTU
Mineralogical nature of suspended matter	minor impact on optimal doses	doses about 50% lower if montmorillonite clays are present (Blue Nile)
Pollution by organic matter	minor impact on optimal doses	great impact on doses and additional organic load
Floc	coarse due to aluminium hydroxides	very fine; result is slower settling; further decrease of settling at lower temperature
Sludge volume	great	small
pH of treated water	increase of acidity (effect of SO ₄ ²⁻)	no change
Hardness	increase of Ca ²⁺ due to neutralisation	no change

Preparation and application of Moringa seed coagulants

Seed quality

Only ripe *Moringa oleifera* seeds (with brown seed coat) give a high coagulant efficiency (Jahn, 1986). Improper treatment of the seeds leads to loss of coagulation capacity. It can be prevented if collection and treatment is done by agro-foresters or trained women and by using correct equipment.

Turbidity range

Experiences with seed coagulation relate to highly turbid waters only. If **optimal doses** and **proper stirring** are applied, seed extracts of *Moringa oleifera* can also reduce low turbidity levels to 5-10 NTU after one hour of settling. For raw water with turbidity below 30 NTU, alum is superior in performance (table 14.2). Thus, surface waters with varying turbidity (below 30 NTU for certain periods of the year) cannot always be treated adequately with seed extracts alone but need coagulant aids during such low turbidity periods. Use of coagulant aids is not feasible at household level.

Chemical water quality

Seed coagulants are more sensitive than alum to the mineralogical composition of suspended matter. Waters polluted by organic matter are only suitable for long-term treatment as long as the required seed coagulant dose is less than 250 mg/l. This is for both economic and microbiological considerations.

Climatic factors

Seed coagulants are mainly applicable as primary coagulants for tropical and subtropical countries. At low temperatures the settling of the fine flocs (table 14.2) is too slow and incomplete, unless seed treatment is combined with other coagulants.

Removal of pathogens

Like alum, Moringa seed extracts achieve a removal of faecal coliforms of more than 98% under optimal conditions. However, if the residual turbidity is more than 30-40 NTU, the treated water still has the same contamination as raw water. Therefore, optimal dosing is required for small plants and for household application.

Determination of optimal doses

Simplified ("village") jar tests are a convenient alternative where the usual measurements cannot be afforded or electricity is not available. Special devices have been designed for stirring the seed coagulant at plant level. A seed coagulant suspension has different reaction properties than a solution of a purified chemical such as alum. The coagulant efficiency is strongly reduced by shortening the time needed for thorough mixing of the seed extract with turbid water.

Involvement of women, teachers and commerce

Asian and African women from the lower classes are mainly responsible for the discovery of seed extracts as coagulants for turbid water. Lack of knowledge on application has limited the possible improvement of water quality. Water coagulation at household level cannot be learned from a demonstration alone. Therefore, the involvement of teachers or commercial outlets is required to help the women in determining the optimal seed coagulant dose, and to distribute or sell standard solutions of the seed coagulant.

Socio-economic challenges

Since Moringa oleifera is a multipurpose tree, certain economic interests may endanger long-term uses of seed extracts for water coagulation. Sometimes people prefer to have the fruit trees in their own gardens rather than on community lands (women then have no right to harvest the seeds). There may also be a commercial preference to sell green Moringa pods as a delicacy to urban customers or factories. On the other hand, removal of the seed oil for other uses and application of press cake extracts instead of seed extracts has been tried out in small plants of Malawi and Tanzania (Folkard et al., 1993). There are commercial developments too in the production of a completely biodegradable Moringa coagulant, known under the commercial name Phytofloc™.

14.4 Rapid mixing

Rapid mixing aims at the immediate dispersal of the entire dose of chemicals throughout the mass of the raw water. To achieve this, it is necessary to agitate the water violently and to inject the chemical in the most turbulent zone, in order to ensure its uniform and rapid dispersal.

The mixing has to be rapid, because the hydrolysis of the coagulant is almost instantaneous (within a few seconds). The destabilisation of colloids also takes a similar short time.

The location of the rapid mixer should be near to the “chemical house” where solutions of chemicals are prepared. The feeding pipes then will be of short length. It is also desirable to place the rapid mixing device close to the flocculators. To combine both these requirements in the layout of a treatment plant is often quite difficult.

Many devices are used to provide rapid mixing for the dispersal of chemicals in water. Basically, there are two groups:

- Hydraulic rapid mixing
- Mechanical rapid mixing

Hydraulic rapid mixing

For hydraulic rapid mixing, arrangements are used such as channels or chambers with baffles producing turbulent flow conditions, overflow weirs, and hydraulic jumps (Figs. 14.3; 14.4; 14.5). Rapid mixing may also be achieved by feeding the chemicals at the suction side of pumps. With a good design, a hydraulic mixer can be as effective as a mechanical mixing device.

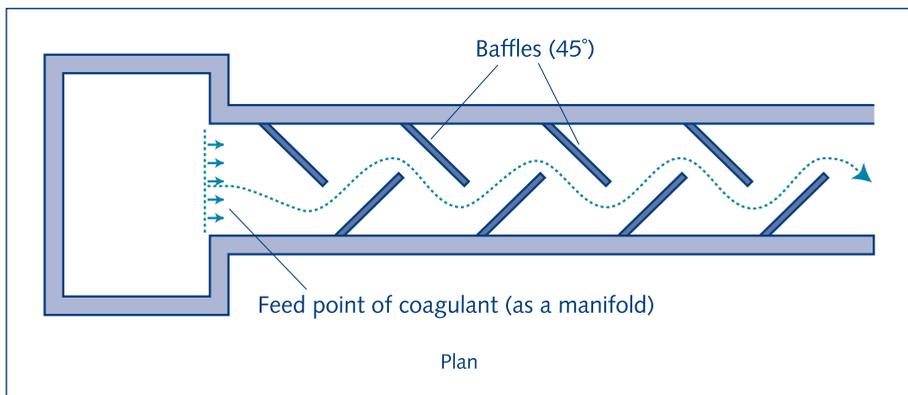


Fig. 14.3. Baffled channel for rapid mixing (not very effective)

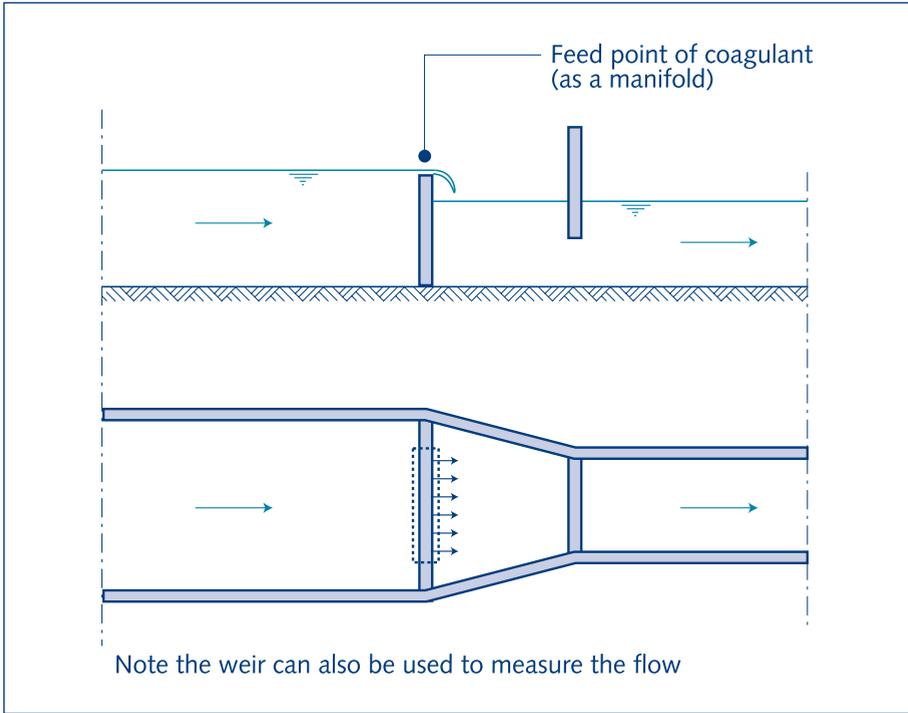


Fig. 14.4. Overflow weir

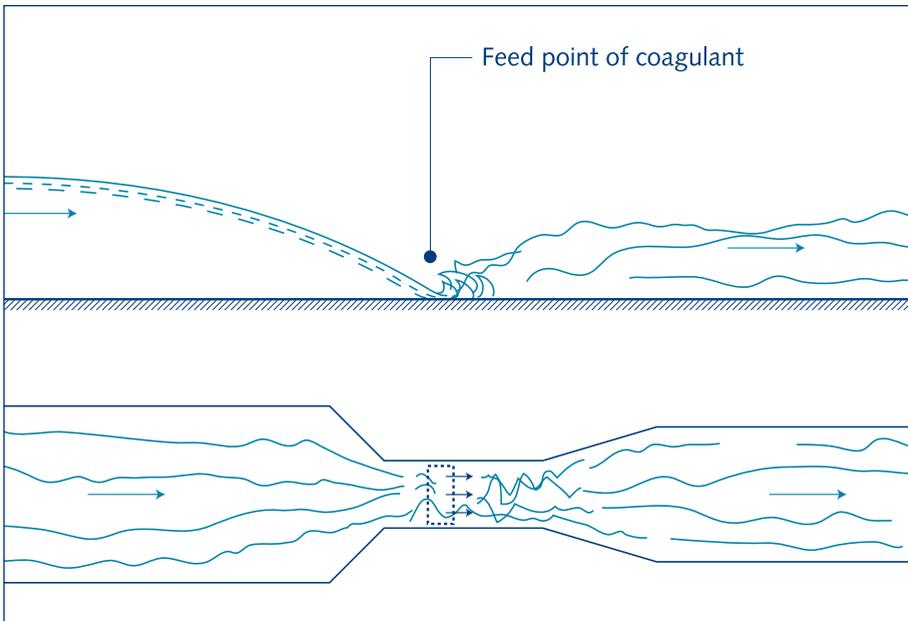


Fig. 14.5. Hydraulic jump

Mechanical rapid mixing

With mechanical mixing the power required for agitation of water is imparted by impellers, propellers or turbines (*rapid mixers*, *flash mixers*, and *turbo mixers*). See figure 14.6.

Generally mechanical rapid mixers are less suitable for small treatment plants than hydraulic ones since they require a reliable and continuous supply of power and maintenance.

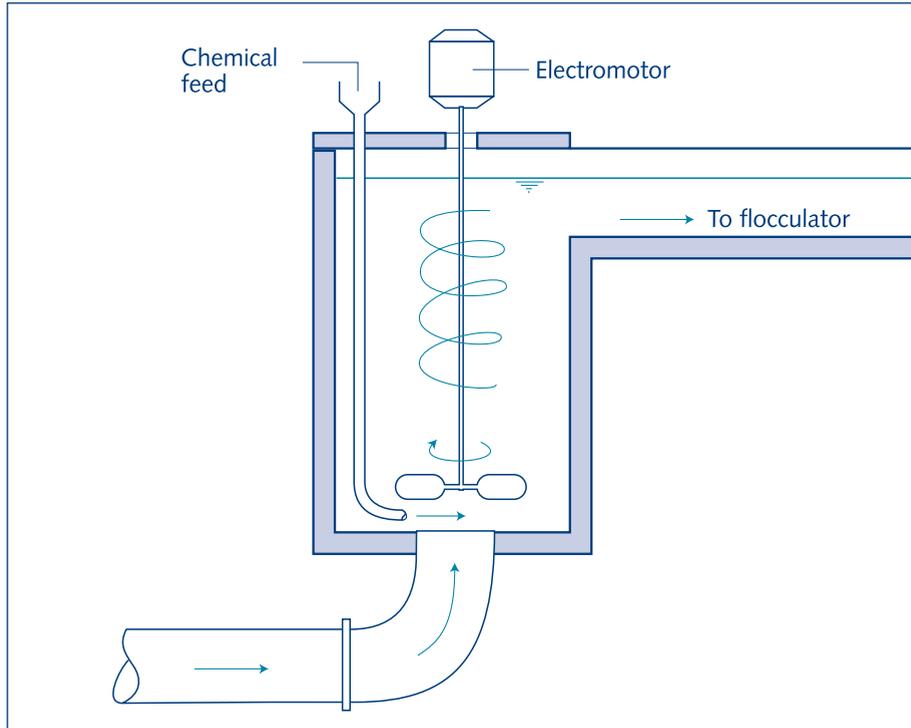


Fig. 14.6. Mechanical mixer

14.5 Flocculation

Flocculation is the process of gentle and continuous stirring of coagulated water for the purpose of forming flocs through the aggregation of the minute particles present in the water. It is thus the conditioning of water to form flocs that can be readily removed by settling, dissolved air flotation or filtration. The efficiency of the flocculation process is largely determined by the number of collisions between the minute coagulated particles per unit of time. There are mechanical and hydraulic flocculators.

In mechanical flocculators the stirring of the water is achieved with devices such as paddles, paddle reels or rakes.

These devices can be fitted to a vertical or horizontal shaft. Vertical shaft flocculators are usually placed in a square tank with several chambers (four or more). They have the advantage of having only bearing in the water, and no gland is necessary as the motor and gearing are above the water. With horizontal shaft flocculators having a traverse flow, one should provide at least four rows of shafts, with partitions of baffles (stop logs), so as to avoid short-circuiting.

In hydraulic flocculators the flow of the water is so influenced by small hydraulic structures that a stirring action results. Typical examples are channels with baffles, flocculator chambers placed in series (e.g. *Alabama*-type flocculator) and gravel bed flocculators.

The main shortcomings of hydraulic flocculators are:

- No adjustment is possible to changes of raw water composition.
- No adjustment is possible to the water production rate of the treatment plant.
- The head loss is often appreciable.
- They may be difficult to clean.

Their advantages are that they have no motor power, electric cables switchgear, etc. to maintain and general maintenance is easier.

Design of flocculators

In the design of a flocculator installation not only the velocity gradient (G) should be taken into account, but also the detention time (t). The product $G.t$ gives a measure for the number of particle collisions, and thus for the floc formation action⁵.

The equation for computing the velocity gradient is: $G = (P/(V.m))^{1/2}$ in which

G = velocity gradient (s^{-1})

P = power transmitted to the water (watt = $rg hQ$)

r = density of water = 1000 kg/m^3

g = gravitational acceleration = 9.81 m/s^2

h = head loss of the water passing through the flocculator in m

Q = volumetric flow rate in m^3/s

V = volume of water to which the power is applied; where applicable, the volume of the mixing tank or basin (m^3)

m = dynamic viscosity of water (kg/m.s), see table 14.3

5 Scientifically the complete dimensionless group is $G.t.C$. where C = concentration volume/volume of floc particles in the water. But in the types of mechanical and hydraulic flocculators described here, which are flow-through (that is, no flocs are retained) the value of C is very small and usually ignored. C becomes more important in flocculators where the floc is retained by recirculation or in suspension as a floc blanket. Operationally these are not suitable for small community water supplies.

Table 14.3 Dynamic viscosity of water μ (kg/m.s)

Temperature $t(^{\circ}\text{C})$	15	20	25
Dynamic viscosity μ (kg/m.s)	1.14×10^{-3}	1.01×10^{-3}	0.96×10^{-3}

Table 14.4 Flocculator design criteria

Design factor	G (s^{-1})	t (s)	$G.t$
Range	10-100	1 200-1 800	30 000-150 000
Typical value	45-90	1 800	50 000-100 000

For each individual flocculator the optimal $G.t$ value should be carefully selected, and taken as high as is consistent with the optimal formation of flocs without causing disruption or disintegration of the flocs after they have formed. Chemicals such as activated silica or polyelectrolytes (coagulant aids) can improve the internal cohesion of the flocs.

14.6 Hydraulic flocculators

Baffled channel flocculators

For horizontal-flow baffled flocculation channels (Fig. 14.7), the design water velocity usually is in the 0.10-0.30 m/s range. Detention time normally is 15-20 minutes.

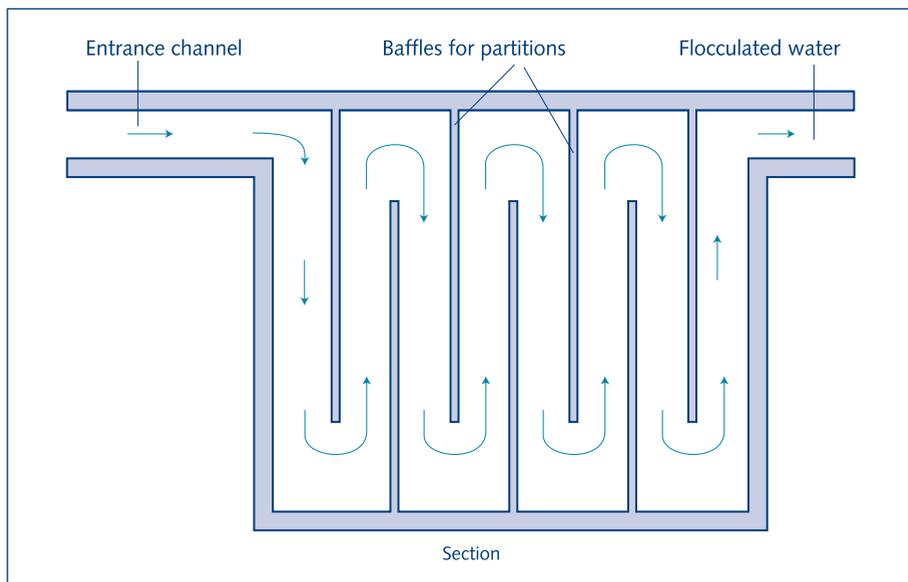


Fig. 14.7. Horizontal-flow baffled channel flocculator (plan)

This type of flocculator is well suited for very small treatment plants. The efficiency, however, is highly dependent on the depth of water in the baffled channel.

Flocculators with vertical flow through baffled chambers (Fig. 14.8) are mostly used for medium and larger-size water treatment plants. The water flow velocity range is 0.1-0.2 m/s. Detention time is 10-20 minutes. Cleaning arrangements are called for because of deposits in the flocculator.

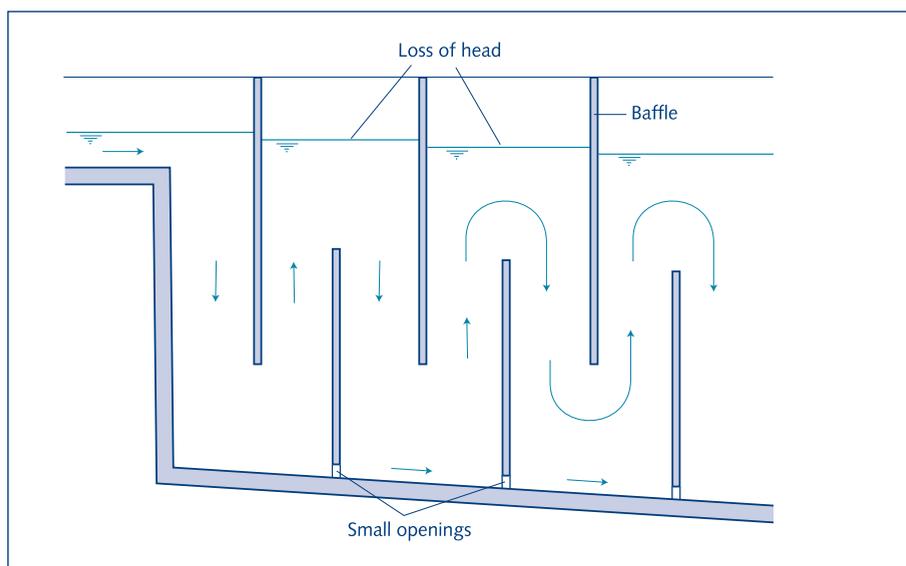


Fig. 14.8. Vertical-flow baffled chamber flocculator (cross-section)

Alabama-type flocculators

Alabama-type flocculators are hydraulic flocculators having separate chambers placed in series through which the water flows in two directions (Fig. 14.9). The water flows from one chamber to the next, entering each adjacent partition at the bottom end through outlets turned upwards. This type of flocculator was initially developed and used in the state of Alabama (U.S.A.) and later introduced in Latin America.

For effective flocculation in each chamber, the outlets should be placed at a depth of about 2.50 m below the water level.

Common design criteria are:

Rated capacity per unit chamber:	25-50 l/s per square metre
Velocity at turns	0.40-0.60 m/s
Length of unit chamber (L)	0.75-1.50 m
Width (B)	0.50-1.25 m
Depth (h)	2.50-3.50 m
Detention time (t)	15-25 minutes

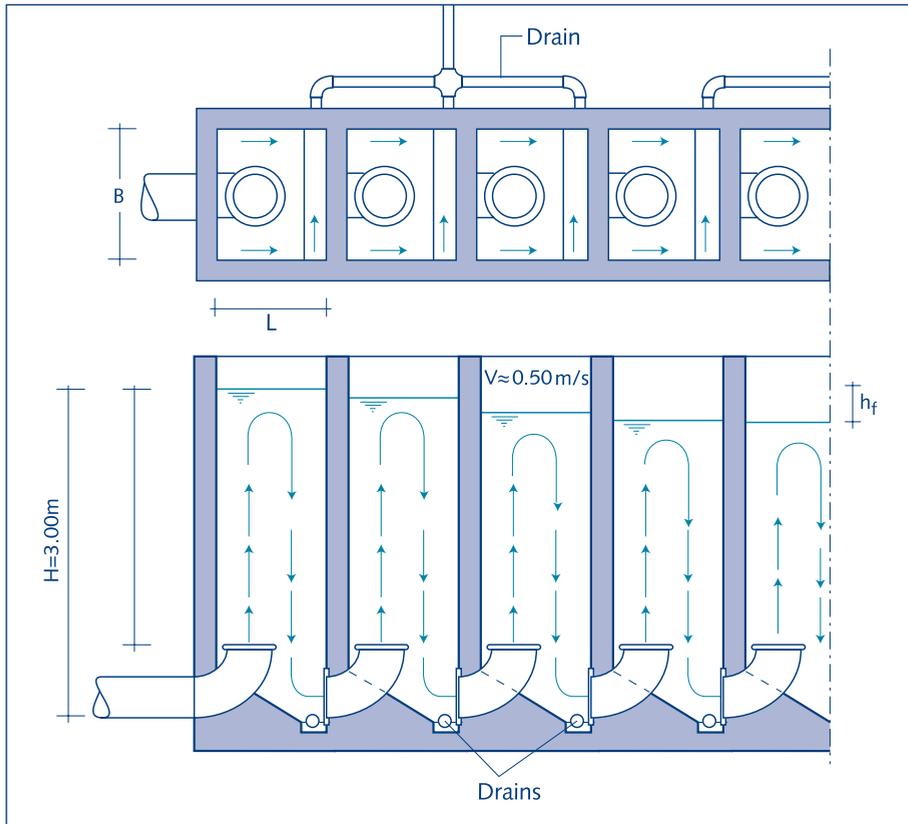


Fig. 14.9. Alabama-type flocculator

The loss of head in this type of flocculator normally is about 0.35-0.50 m for the entire unit. The velocity gradient is usually in the 40-50 s^{-1} range.

Table 14.5 provides practical guidance for the design of an *Alabama*-type flocculator.

Example:

Flow $Q = 1.2 \text{ m}^3/\text{minute}$. Detention time = 15 mm. Size of curved pipe: 250 mm (10").

Unit chamber measures $0.60 \times 0.75 \text{ m}^2$. Volume of unit chamber: 1.3 m^3 .

Total volume required. $15 \times 1.2 = 18 \text{ m}^3$ Number of chambers $18/1.3 = 14$.

Hydraulic jet mixer and flocculator

In a jet flocculator the coagulant (alum) is injected in the raw water using a special orifice device. The water is then jetted into a tapered cylinder placed above the nozzle. The resulting jet pump action gives a gentle stirring of the water for floc formation, and part of the formed flocs are recycled (Fig. 14.10). Through the combination of these two actions excellent flocculation results can be achieved.

Table 14.5 Guidance for *Alabama-type* flocculator design

Flow Rate Q (l/s)	Width B (m)	Length L (m)	Diameter D (mm)	Unit chamber area (m ²)	Unit chamber volume (m ³)
10	0.60	0.60	150	0.35	1.1
20	0.60	0.75	250	0.45	1.3
30	0.70	0.85	300	0.6	1.8
40	0.80	1.00	350	0.8	2.4
50	0.90	1.10	350	1.0	3.0
60	1.00	1.20	400	1.2	3.6
70	1.05	1.35	450	1.4	4.2
80	1.15	1.40	450	1.6	4.8
90	1.20	1.50	500	1.8	5.4
100	1.25	1.60	500	2.0	6.0

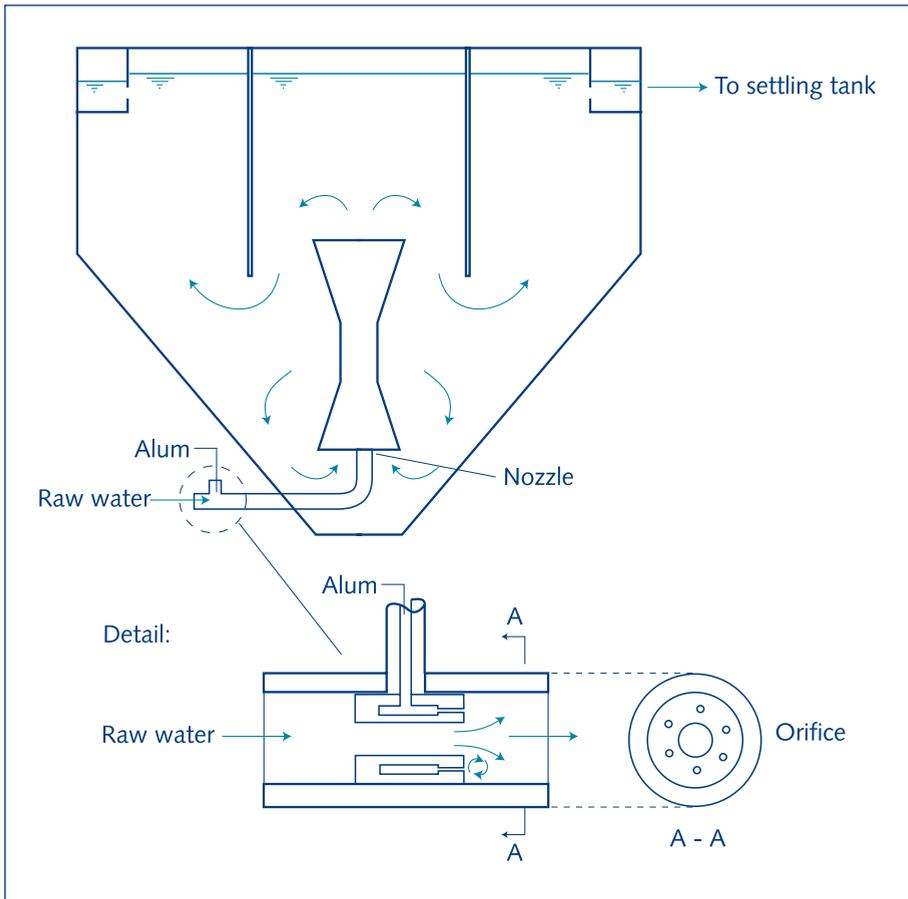


Fig. 14.10. Hydraulic jet flocculator

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Web sites

Water Treatment Plant Operation (training programme):
<http://www.owp.csus.edu/WTPO1.html>