

## Chapter 2

# Processes Design

**Keywords** Coagulation • Flocculation • Sedimentation • Clarification system • Filter • Ion exchange • Demineralizing unit • Reverse osmosis • Electrodialysis

Industrial raw water treatment is used to optimize most water-based industrial processes, such as heating, cooling, processing, cleaning and rinsing processes. The ultimate goal is to reduce operating costs and risks. Poor water treatment can cause serious damage to the process and the final results. Surfaces of pipes and vessels can be affected by corrosion, and steam boilers can scale up or corrode [52].

The suspended particles in water vary considerably in source, composition, charge, particle size, shape and density. The smaller particles present in water are kept in suspension by the action of physical forces on the particles themselves. Figure 2.1 shows an overview of the water treatment process:

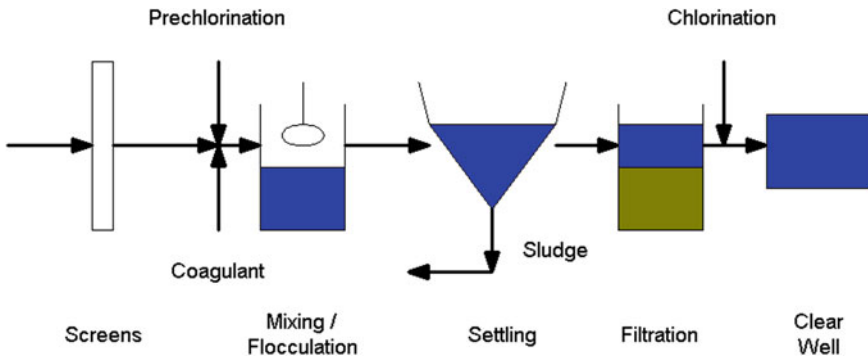
The water treatment process consists of several steps:

### **Coagulation and flocculation**

Coagulation and flocculation processes are used to separate the suspended solids (SS) portion from the water. Raw water from terminal reservoirs is drawn into mixing basins at our treatment plants where we add alum, polymer and sometimes lime and carbon dioxide. This process causes small particles to stick to one another, forming larger particles [53–56].

Coagulation and flocculation occur in successive steps intended to overcome the forces stabilizing the suspended particles, allowing particle collision and growth of floc. The purpose of coagulation and flocculation is to cause small pollutant particles such as metals to aggregate and form large enough floc, so that they can be separated from the wastewater through sedimentation.

There are three main types of coagulants that are used to overcome the repulsive forces of particles, thus causing them to aggregate. Electrolytes, organic polymers and synthetic polyelectrolytes are added to wastewater, and then



**Fig. 2.1** An overview on water treatment process

flocculation tanks mix the water to promote flocs and subsequent physical separation [57–59].

Each of these processes is briefly explained in below Figs. 2.2 and 2.3:

### **Sedimentation**

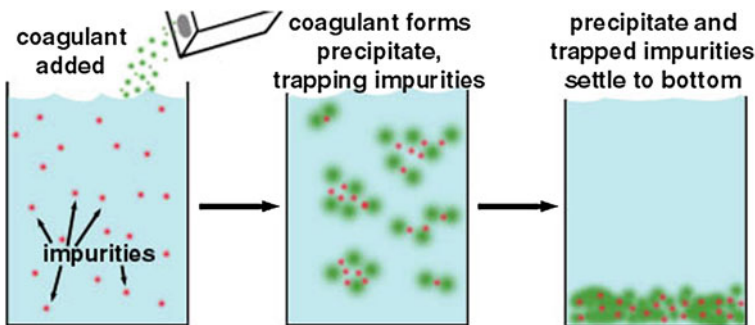
Over time, the now-larger particles become heavy enough to settle to the bottom of a basin from which sediment is removed.

### **Filtration**

The water is then filtered through layers of fine, granulated materials—either sand or sand and coal, depending on the treatment plant. As smaller, suspended particles are removed, turbidity diminishes and clear water emerges [59–61].

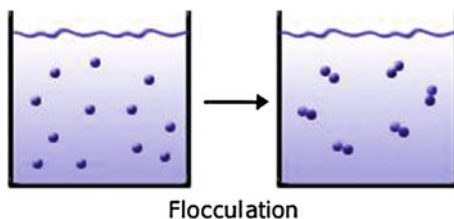
### **Disinfection**

To protect against any bacteria, viruses and other microbes that might remain, disinfectant is added before the water flows into underground reservoirs throughout the distribution system and into your home or business. Denver Water carefully monitors the amount of disinfectant added to maintain quality of the water at the farthest reaches of the system. Fluoride occurs naturally in our water but also is added to treated water [61–63].



**Fig. 2.2** Schematic of coagulation process

**Fig. 2.3** Schematic of flocculation process



### **Corrosion control**

pH is maintained by adding alkaline substances to reduce corrosion in the distribution system and the plumbing in home or business.

## **2.1 Coagulation and Flocculation**

### **2.1.1 General Information**

In modern water treatment, coagulation and flocculation are still essential components of the overall suite of treatment processes. Coagulation is always considered along with flocculation and is used to remove particles which cannot be removed by sedimentation or filtration alone. These particles are usually less than 1  $\mu\text{m}$  in size and are termed colloids. They have poor settling characteristics and are responsible for the color and turbidity of water. They include clays, metal oxides, proteins, microorganisms and organic substances such as those that give the brown coloration to water from “peaty” catchment areas. The important property which they all have is that they carry a negative charge and this, along with the interaction between the colloidal particles and the water, prevents them from aggregating and settling in still water. The particles can be aggregated by adding either multivalent ions or colloids having an opposite (positive) charge. These are added as chemical coagulants [61–64].

Chemicals commonly used as coagulants in water treatment are aluminum and ferric salts which are present as the ions  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$ . These positively charged multivalent ions neutralize the naturally occurring negatively charged particles, thus allowing the particles to aggregate. At high concentrations of aluminum or ferric salts, and in the presence of sufficient alkalinity, insoluble hydroxides of aluminum or iron are formed (see below). In the precipitation reaction, the colloidal particles are enmeshed within the precipitate and thus removed [62–66].

In water treatment, coagulation is defined as a process by which colloidal particles are destabilized and is achieved mainly by neutralizing their electric charge. The product used for this neutralizing is called a coagulant.

Flocculation is the massing together of discharged particles as they are brought into contact with one another by stirring. This leads the formation of flakes or floc. Certain products, called flocculating agents, may promote the formation of floc.

Separation of the floc from the water can be achieved by filtration alone or by settling [67–71].

Rate of flocculation is dependent upon many factors including concentration of particles, particle contact and range of particle sizes. Coagulation targets dissolved ions such as metal and radionuclides. Some difficulties with this technology include the frequent need to adjust pH levels, the creation of toxic sludge that must be eventually mitigated, and the difficulty that results in trying to address the chemical nature of multiple compounds. This technology has been used consistently in the electronics and electroplating industry as well as for applications in groundwater treatment [63–69].

Coagulation and flocculation are frequently used in the treatment of potable water and preparation of process water used by industry. Certain dissolved substances can also be adsorbed into the floc (organic matter, various pollutants, etc.) [62–64].

### ***2.1.2 Main Coagulants***

The most widely used coagulants are based on aluminum or iron salts. The commonly used metal coagulants fall into two general categories: those based on aluminum and those based on iron. The aluminum coagulants include aluminum sulfate, aluminum chloride and sodium aluminate. The iron coagulants include ferric sulfate, ferrous sulfate, ferric chloride and ferric chloride sulfate. Other chemicals used as coagulants include hydrated lime and magnesium carbonate [65–69].

The effectiveness of aluminum and iron coagulants arises principally from their ability to form multi-charged polynuclear complexes with enhanced adsorption characteristics. The nature of the complexes formed may be controlled by the pH of the system.

In certain cases, synthetic products, such as cation polyelectrolytes, can be used. Cation polyelectrolytes are generally used in combination with metal salt, greatly reducing the salt dosage which would have been necessary. Sometimes no salts at all are necessary, and this greatly reduces the volume of sludge produced [65–68].

### ***2.1.3 pH Value for Coagulation and Dosage***

Removal of turbidity, suspended solids (SS) and natural organic matter (NOM) using coagulation is well known because of the ability of the process in destabilizing the colloids particles and reducing the repulsion force between the particles. For any water, there is an optimum pH value, where good flocculation occurs in the shortest time with the least amount of chemical. For actual application of coagulating agents, the dosage and optimum pH range should be determined by coagulation control or a jar test [60–63].

### 2.1.4 Choice of Coagulant

Coagulant should be chosen after the raw water examination in laboratory by means of flocculation test while considering following factors [61–66]:

- (a) Nature and quantity of the raw water.
- (b) Variations in the quality of the raw water (daily or seasonal especially with regard to temperature).
- (c) Quality requirements and use of the treated water.
- (d) Nature of the treatment after coagulation (filter coagulation, settling).
- (e) Degree of purity of reagents, particularly in the case of potable water.

The chemistry of coagulation/flocculation consists of three processes—flash mix, coagulation and flocculation.

## 2.2 Sedimentation

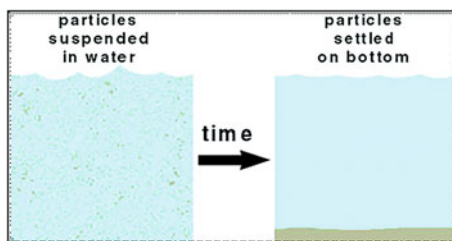
When water has little or no movement, SS sink to the bottom under the force of gravity and form sediment. The process by which suspended or coagulated material separates from water by gravity is called sedimentation. Sedimentation is recommended as simple pre-treatment of water prior to application of other purification treatments such as filtration and disinfection methods. It removes undesirable small particulate suspended matters (sand, silt and clay) and some biological contaminants from water under the influence of gravity (Fig. 2.4). In water treatment, it is used to remove solids from waters which are high in sediment content and also to remove particles rendered settle able by coagulation and flocculation [55–58].

The theory of sedimentation would seem to be quite simple. If the settling tank is made large enough and the flow slow enough, this will enhance the rate of fall of the sediment toward the bottom of the tank [69–70].

Sedimentation alone is an effective means of water treatment but is made more effective by coagulation.

Pre-sedimentation basins or sand traps are sometimes used when waters to be treated contain large amounts of heavy SS. This decreases the amount of sediment

**Fig. 2.4** A schematic of sedimentation process



which accumulates in the sedimentation basin as a result of the coagulation and sedimentation process. If water is to be filtered in the course of treatment, coagulation and sedimentation will reduce the load on filters.

### ***2.2.1 Type of Sedimentation Tanks***

Sedimentation is used to remove solids from water. It is suitable for water with high sediment content. It is easy to perform and requires a minimum of materials and skill. It can be done with as little as two or more simple storage vessels such as pots and buckets by manual transfer. The effectiveness of a sedimentation tank depends on the settling characteristics of the SS that are to be removed and on the hydraulic characteristics of the settling tank [70–76].

The hydraulic characteristics of a settling tank depend on both the geometry of the tank and the flow through the tank.

Most sedimentation tanks used in water purification today are of the horizontal-flow type. Horizontal-flow tanks may be either rectangular or circular in plan. Circular, horizontal-flow tanks may be either center feed with radial flow, peripheral feed with radial flow or peripheral feed with spiral flow [70–73].

In horizontal-flow tank design, the aim should be to achieve as nearly as possible the ideal condition of equal velocity for all points lying on each vertical line in the settling zone (The ideal basin condition). This in effect would be complete separation of the four zone of the tank.

The sedimentation basins should be equipped with mechanical equipment for continuous removal of settled solids.

### ***2.2.2 Practical Sedimentation Basin***

The size and type of particles to be removed have a significant effect on the operation of the sedimentation tank. Because of their density, sand or silt can be removed very easily. The velocity of the water-flow channel can be slowed to less than one foot per second, and most of the gravel and grit will be removed by simple gravitational forces. In contrast, colloidal material, small particles that stay in suspension and make the water seem cloudy, will not settle until the material is coagulated and flocculated by the addition of a chemical, such as an iron salt or aluminum sulfate. The situation in practical sedimentation basins is modified because of the relative density (specific gravity) and shape of the particles, coagulation of particles, concentration of particles and movement of water through the settling tank.

The relative density of suspended matter may vary from 2.65 for sand to 1.03 for flocculated particles or organic matter and mud containing 95 % water.

Floc particles resulting from coagulation with aluminum compounds have a relative density of about 1.18, and those obtained using ferrous sulfate as a

coagulant have a relative density of 1.34. These values can be increased by clay or silt or decreased by organic matter. However, most of the particles in a settling basin settle at velocities within Stock's law.

Because of the difference in shape, size and relative density of particles, there is a wide range of settling velocities. This results in some subsiding particles overtaking others, thus increasing the natural tendency of suspended matter to flocculate [68–72].

### 2.2.2.1 Factors Influencing the Design of Sedimentation Basins

Several factors affect the separation of settle able solids from water. Some of the more common types of factors to consider are

- Sedimentation basins are often designed on the basis of existing installations which are handling the same type of water.
- Experience and judgment of the engineer are also instrumental in the design. However, there are some important points, other than structure, which should be considered in the design of a basin.
- The basin should be large enough to insure an adequate supply of treated water during periods of peak load.
- The characteristics and type of water treatment also affect the design of the basin. Such things as the nature of the suspended material and the amount and type of coagulant needed, if any, should also be considered.
- The influence of temperature is also important, since the viscosity of the water is less on a warm summer day than in cold weather.
- The number of basins depends upon the amount of water and the effect of shutting a basin down. It is desirable to have more than one basin to provide for alternate shutdown of individual basins for cleaning or repairs.
- Basins vary in shape—square, rectangular and round. However, regardless of shape, most basins have slopping bottoms to facilitate the removal of deposited sludge.

The size and type of particles to be removed have a significant effect on the operation of the sedimentation tank.

The shape of the particle also affects its settling characteristics. A round particle, for example, will settle much more readily than a particle that has ragged or irregular edges.

All particles tend to have a slight electrical charge. Particles with the same charge tend to repel each other. This repelling action keeps the particles from congregating into flocs and settling.

Sedimentation basins are equipped with inlets in order to distribute the water uniformly between the basins and uniformly over the cross section of each basin. Inlet and outlets should be designed to avoid short circuiting through the basin [71–77].

## 2.2.3 Hydraulic Properties of Sedimentation Basin

### 2.2.3.1 Surface Area or Surface Overflow Rate

The surface area of the tank is one of the most important factors that influences sedimentation. For any particular rate of inflow, the surface area provided determines the tank overflow rate,  $v = Q/A$  (see Table 2.1). If there were such a thing as an ideal tank, the tank overflow rate could be made equal to the settling velocity of the particles that the tank was designed to remove.

Because no ideal tank exist, it is customary to reduce the tank overflow rate and to increase the detention time over those indicated by theoretical analysis. It is recommended to apply a correction factor 1–1.25 to both values when settling a discrete solid.

For the sedimentation of flocculent particles from dilute suspensions, the settling velocity will generally be decreased by a factor of 1.25–1.75.

The higher settling velocities or tank overflow rates would be used for warmer water; the lower settling velocities for cold waters.

The settling velocity used in the settling tank design overflow rate is one of the major factors determining tank efficiency [70–78].

### 2.2.3.2 Depth

The theoretical detention time is equal to the volume of the tank divided by the flow rate. Hence, if  $A$  and  $Q$  are constant, the theoretical detention time is directly proportional to the tank depth.

As the performance of the tank depends on the flocculation of the SS, and the degree of flocculation depends on the detention time, the tank performance in removal of flocculent particles will depend on its depth.

The efficiency of removal, however, is not linearly related to the detention time. For example, if 80 % of the SS were removed with a detention time of 2 h, a detention time of 3 h might remove only 90 %.

**Table 2.1** Typical sedimentation tank overflow rates [5–8]

Type of water	Treatment	Overflow rate ( $\text{m}^3/\text{m}^2 \cdot \text{h}$ )
Surface water	Alum floc	0.61–0.93
Surface or ground water	Lime softening	0.93–1.54
	Clarification in upflow units	2.44–4.52
		1.83–2.44 (cold water)
		2.44–3.66 (warm water)
	Softening in upflow units	1.83–6.11
		To 3.06 (surface)
		To 4.40 (well)



The raw water entering a sedimentation tank will have a greater density than the water in the tank, as it will contain more SS.

The heavier influent water will tend to form density currents and move toward the bottom of the tank, where it can interfere with the sedimentation process. Density currents are more apt to occur in deep tanks.

Sedimentation basins are commonly designed to remove solids resulting from chemical coagulation of surface water and lime soda as softening of surface and ground waters. In a properly designed basin, a detention time of from 2 to 4 h is usually sufficient to prepare the water for subsequent filtration. When the water is to be used without filtration, longer detention time (up to 12 h) may be provided [73–79].

### 2.2.3.3 Velocity Through Basin

The velocity of flow through settling basin will not be uniform over the cross section perpendicular to the flow even though the inlets and outlets are designed for uniform distribution. The velocity will not be stable because of density currents and the operation of the sludge removal mechanism. In order to minimize these disturbances, the velocity through a sedimentation tank should be kept between 0.0026 and 0.015 m/s [5–8].

### 2.2.3.4 Inlet and Outlet Conditions

The inlet to a sedimentation tank should be designed to distribute the water uniformly between basins and uniformly over the full cross section of the tank.

The inlet is more effective than the outlet in controlling density and internal currents, and tank performance is effected more by inlet than by outlet conditions.

The best inlet is one that allows the water to enter the settling tank without the use of pipe lines or channels.

The head loss in preamble baffle ports or basin inlet ports should be relatively large compared to the kinetic energy of the water moving past the permeable ports. This is required to assure equal distribution of flow between tanks and between inlet ports [76–80].

As flocculent solids will frequently be involved, the velocities in the influent channels must be kept low, usually between 0.15 and 0.60 m/s, to prevent break up of the floc. Similar low velocities are required through the inlet ports to reduce the danger of inertial currents interfering with sedimentation.

It has been found that relatively minor changes in an inlet can completely change the hydraulic performance of a settling tank.

The main purpose of the inlet is to provide a smooth transition from the relatively high velocities in the influent pipe to the very low uniform velocity distribution desired in the settling zone, in such a way that interference with the settling process is minimal.

**Table 2.2** Typical weir overflow rates [5–8]

Type of service	Weir overflow rate, m <sup>3</sup> /m·h
Water clarification	<26
Water treatment	6–7.5
Light alum floc (low-turbidity water)	
Heavier alum flow (higher-turbidity water)	7.5–11.2
Heavy floc from lime softening	11.2–13.4

The purpose of the outlet is the same except that the transition is from the settling zone to the effluent pipe.

The water level in settling basins is usually controlled at the outlet. This control, however, may be set by means of other than the outlet weir, for example, by a succeeding unit.

It may be desirable to encourage deliberate fluctuation of water level in the settling basins to make use of the storage in them or to break up ice.

Basin outlets are often of the V-notch weir type, and these are quite often provided with means for vertical adjustment to aid in control of overflow. The V-notches help in keeping a uniform flow over the weir at low water levels.

The effect of weir rates, cubic meters per hour per meter of weir, on sedimentation, is not well known, but weir rates are usually limited to commonly accepted values (see Table 2.2).

Circular basins with the inlet at one side and the outlet on the opposite side are not very efficient because of dead areas in the tank and short circuiting of water flow across the tank. The efficiency of circular tanks is much greater if the water is fed to the tank from an inverted siphon located in the center of the tank, and the effluent taken from a weir passing around the entire periphery.

Square basin may be operated in the same manner or may be fed from one side with effluent removed from the opposite side.

The use of baffles in sedimentation tanks should be limited to the inlets and outlets and as remedial measures in poorly designed tanks [77–82].

### 2.2.3.5 Sludge Handling

The bottom of a settling tank is normally sloped gently toward a sludge hopper where the sludge is collected. The sludge usually moves hydraulically toward the hopper. Sludge scraper mechanisms are used to prevent the sludge from sticking to the bottom and to help its flow.

The sloping bottom and the sludge hopper provide a certain amount of storage space for the sludge before it is removed. The movement of the sludge scraper mechanism should be quite slow so as not to disrupt the settling process or to resuspend the settled sludge. The velocity of the scrapers should be kept below 18.3 m/h for this reason. Some mechanisms in circular tanks carry vacuum suction pipes instead of squeegees for removing relatively light, uniform solids [78–81].

## 2.3 Clarification Systems

The equipment used for clarification can be many types; however, the equipment used should provide the correct environment to carry out each step coagulation, flocculation and sedimentation.

Older design for clarification units provided separate chemical addition, flash mixing, flocculating and settling facilities. Modern combined units provide all three steps in one unit, such as sludge recirculation (solids contact) type or sludge blanket unit.

In theory, the sludge blanket unit provides better clarification than the sludge recirculation type as a result of filtering action provided by the sludge bed and the gentle handling of the flocs.

A basic clarification system consists of the clarifier and a chemical feeding system which meters chemical additives in proportion to flow.

The size of standard clarification unit is based upon an upflow rate of approximately  $2.5 \text{ m}^3/\text{m}^2\cdot\text{h}$  (1.2–3.7 range), with a total retention time of 1.5–4 h. The clarified water will contain approximately 5–10 mg/kg of suspended matter [5–8].

Design criteria of clarifiers should be based on steady operation at maximum load. However, it is expected that the actual load will fluctuate over the range from 10 to 100 % of design flow rate and the clarifier should have the capacity to perform satisfactory under these conditions.

Consideration should also be given to anticipation of flow rate limitations and chemical dosages during difficult treatment periods considering high turbidity, low temperature and/or polluted conditions. Manufacturer shall either take such potential difficulties into consideration in design or state the limitations imposed by such conditions [79–83].

## 2.4 Filters for Water Treating Systems

Multiple units shall be provided to allow continuous operation at full system design capacity with two units out of service (for example, one unit shut down for maintenance and one unit in backwash mode).

Design service flow rates shall be as described in Table 2.3.

Air securing shall be used for units treating effluent at temperatures less than  $93^\circ\text{C}$ . The design air scour rate shall be  $90 \text{ m}^3/\text{m}^2\cdot\text{h}$  minimum. If plant air is unavailable, a separate air compressor shall be included within the system.

Subsurface washers shall be furnished for units treating effluent at temperatures  $93^\circ\text{C}$  and greater. Subsurface wash rate shall be  $12.3 \text{ m}^3/\text{m}^2\cdot\text{h}$ , and minimum design backwash rate can be found in the following Table 2.4.

**Table 2.3** Flow rates in different types of water filters

Unit	Flow rate (maximum with one unit backwashing) (m <sup>3</sup> /m <sup>2</sup> ·h)
Downflow, cold pressure type (<65 °C)	9.7
Downflow, hot pressure type (>65 °C)	10.8
Downflow, gravity type	9.7

**Table 2.4** Minimum backwash rates in different types of water filters

Filter media	Minimum backwash rate m <sup>3</sup> /m <sup>2</sup> ·h
Sand	36.7
Anthracite coal	29.2
Activated carbon	24.5

Bed depth in filters shall be 750 mm minimum. For “in-depth” filters, at least two different density media, of different sizes, shall be furnished.

For hot pressure type units, only washed anthracite coal should be used.

Freeboard shall be a minimum of two-thirds total bed depth, measured from the top of the filter media to the tangent line at the top of vessel.

Filter media traps shall be furnished on the outlet of each pressure filter unit to prevent filter media from entering downstream equipment in the event of under-drain failure. Maximum pressure drop through the trap shall not exceed 35 kPa when the unit is operating at maximum design flow rate. Characteristics of potable water filters should be as per Table 2.5.

Anthracite or marble should be used instead of quartz sand, when any trace of silica must be avoided in industrial process or when they are easier to obtain.

## 2.5 Quantities of SS which can be Removed by Filtration

The following consideration should be made as a guiding principle:

The SS lodge between the grains of the filter material. Since sufficient space should always be left for the water to percolate, the sludge should not, on average, fill more than one quarter of the total volume of voids in the material.

Irrespective of grain size, one cubic meter of filtering material contains about 0.45 m<sup>3</sup> of voids, the volume available for the retention of particles is about 0.11 m<sup>3</sup>, provided that the effective grain size of the filtering medium is suitable to the nature of the particles [80–84].

When the SS are based on colloidal floc, their dry matter content does not exceed 10 kg/m<sup>3</sup>; the quantity that can be removed per m<sup>3</sup> of filter material is therefore no more than  $0.11 \times 10 = 1.1$  kg.

**Table 2.5** Characteristics of potable water filters [5–8]

Filter type	Permissible filtration rates (m <sup>3</sup> /m <sup>2</sup> -h)		Design pretreatment to reduce turbidity in applied water to (mg/kg)		Head required (m)		Length of filter run (h)		Min. thickness (mm)		
	Maximum	day	Maximum rate	Average	Maximum	Clean filter	Maximum	Average	Minimum	Gravel	Sand
Rapid sand gravity	4.9		12.2	2	5	0.3	2.4	36	5	304.8	508
	4.9		12.2	2	5	0.3	7.6	48	5	304.8	609.6
Pressure											
Slow sand	2.4		7.3	1	3	0.6	1.2	1,000	250	304.8	1,066.8
Diatomite	2.4		7.3	1	3	2.1	21.3	6	0.5	304.8	

## 2.6 Process Used for Boiler Feedwater Treatment

Vessel should be of sludge blanket type employing a central downcomer. Separate (not integral) deaerator compartment is preferred. The treater should be so sized that the rising rate of settled water is such that effluent treated water has a turbidity of less than 10 mg/kg.

Separate clean and dirty backwash compartments shall be sized to meet normal filter backwash and sodium zeolite regeneration requirements without increasing flow rate through the unit to more than 10 % of normal design.

The clean backwash water compartment should be replenished by filtered water at a much slower rate than the backwash rate.

The dirty backwash water should be returned at a set rate, so that heat and water are recovered. The treatment should be carried out at low pressure corresponding to vapor pressure for temperatures chosen between 102 and 115 °C as required. Units shall be designed for continuous service and uninterrupted operation for a period of 2 years.

All equipment shall be suitable for unsheltered outdoor installation for the climatic zone specified. The total detention time of the vessel should not be less than 90 min at rated capacity of flow [81–85].

The maximum allowable upflow rate (rinse rate) through the unit shall be  $3.7 \text{ m}^3/\text{m}^2\cdot\text{h}$  at water temperatures above 90 °C. This rate shall not be exceeded when backwashing filters rinsing softeners.

This rate shall be reduced to  $1.0 \text{ m}^3/\text{m}^2\cdot\text{h}$  or less for waters containing appreciable organic matter turbidity or magnesium to meet guaranteed effluent turbidity of less than 10 nephelometric\* units for a range of 10–100 % of design raw water throughput. Chemical mix tanks and pumps should be provided for hot-process treater. Incoming water should be provided at pressure sufficient to overcome the following losses [5–8]:

- pipe friction;
- static head to the top of the softener;
- vent condenser;
- spray nozzle;
- water flow meter;
- water level control valve; and
- vessel operating pressure (exhaust steam pressure).

## 2.7 Ion Exchange

Ion-exchange resins are used to replace the magnesium and calcium ions found in hard water with sodium ions. When the resin is fresh, it contains sodium ions at its active sites. When in contact with a solution containing magnesium and calcium ions (but a low concentration of sodium ions), the magnesium and calcium ions

preferentially migrate out of solution to the active sites on the resin, being replaced in solution by sodium ions. This process reaches equilibrium with a much lower concentration of magnesium and calcium ions in solution than was started with. Ion-exchange resins are used to remove poisonous (e.g., copper) and heavy metal (e.g., lead or cadmium) ions from solution, replacing them with more innocuous ions, such as sodium and potassium.

### 2.7.1 Classification of Ion Exchange Resins

Ion exchange resins are classified according to their specific application as per Table 2.6.

### 2.7.2 Design Criteria for an Ion Exchange System

Design criteria for an ion exchange system should be based upon [5–8]:

- the required flow rate;
- influent water quality,

**Table 2.6** Classification of ion exchange resins [5–8]

Type	Application	Ionic form in the ready-to-use condition	Regenerating agent. Aqueous solution of
Cation exchange resins strongly acidic	Reduction of calcium ion concentration	Na	NaCl
Cation exchange resins strongly acidic	Reduction of salt content	H	HCl, H <sub>2</sub> SO <sub>4</sub>
Weakly acidic	Reduction of hydrogen carbonate concentration	H	HCl, H <sub>2</sub> SO <sub>4</sub> , CO <sub>2</sub>
Weakly acidic	Reduction of heavy metal ion content	Na, H	HCl, H <sub>2</sub> SO <sub>4</sub> , NaOH
Anion exchange resins strongly basic	Reduction of salt content	OH	NaOH
Anion exchange resins strongly basic	Reduction of the content of certain ions, for example, nitrate ions, sulfate ions	Cl, HCO <sub>3</sub>	NaCl, NaHCO <sub>3</sub>
Anion exchange resins strongly basic	Reduction of the organic substance content, for example, humic acids	Cl, OH	NaCl, NaOH
Weakly basic	Reduction of salt content	Free base	NaOH
Weakly basic	Reduction of heavy metal ion content	Free base	NaOH
Weakly basic	Reduction of the organic substance content, for example, humic acids	Free base	NaOH

- desired effluent water quality;
- exchange capacity and hydraulic characteristics of the exchanger;
- period between regenerations;
- type of operation manual or automatic; and
- flexibility required, that is, the number of softener units.

The ion exchangers are not economically suitable for demineralizing waters containing more than 1,000–2,000 mg/kg of dissolved solids, except in a few specialized industrial applications.

The process of ion exchange for softening waters is preferable to precipitation process when one or more of the following conditions exist:

- less than 100 mg/kg of hardness expressed as calcium carbonate is present in the water;
- an extremely low dissolved solids content is required;
- only a limited volume of treated water is required.

Relative exchange capacity of cation exchangers and regenerative salt dosage would be as per Table 2.7.

The anion exchangers have typically an exchange capacity calculated as  $\text{CaCO}_3$  of 27.4–57.2 g/L at a sodium dosage of 1.05–7 kg/kg removed. Interstate degasification in demineralization systems should be considered at flow over 22.7 m<sup>3</sup>/h and alkalinity over 100 mg/kg.

When ultra-pure water is required, using the mixed bed demineralizer is recommended.

The demineralized water storage(s) shall be designed in order to store the produced demineralized water and to cover the following users:

- Make-up to deaerators.
- Process units.
- Regeneration of condensate treatment.

**Table 2.7** Relative exchange capacity of cation exchangers [5–8]

Cation exchanger	Nominal exchange capacity (g/L)	Regenerative salt dosage	
		Volumetric (kg/m <sup>3</sup> )	Effective (kg/kg) hardness removed
Greensand	6.4	20.2	3.1
Processed greensand	12.6	39.5	3.1
Synthetic siliceous zeolite	25.2	79.2	3.1
Resin, polystyrene	73.2	201.7	3.1
Resin, polystyrene	50.3	80	1.7



## 2.8 Standard Specification of Demineralizing Unit

This section specification covers the general requirements for the design, construction and inspection of automatic regenerating type demineralizing units for the production of boiler feedwater.

### 2.8.1 *The Demineralizing Unit Design*

The demineralizing unit shall consist of but not necessarily be limited to the following equipment:

- Cation resin bed for exchanging acidic hydrogen.
- Anion resin bed for exchanging basic hydroxide.
- Degasifier (decarbonator) removing carbon dioxide formed in the cation resin bed, if required.
- Mixed bed polisher containing strong cation and anion resin for exchanging acidic hydrogen and basic hydroxide, respectively, if required.
- Regenerating equipment including chemical storage tanks, measuring tanks, pumps, blowers, instrumentation for control, neutralizing equipment for regeneration-effluent, interconnecting piping and others [76–82].

### 2.8.2 *Chemical for Resin Regeneration*

The following chemicals shall be used for the regeneration of resin:

- $\text{H}_2\text{SO}_4$  or  $\text{HCl}$  solution for cation exchanger.
- $\text{NaOH}$  solution of anion exchanger.
- Skid-mounted chemical storage tanks shall be provided and equipped with a chemical transfer pump for regeneration purposes.
- The capacity of each chemical storage tank shall be designed to enable maximum operation within five cycles.

Two separate chemical transfer pumps shall be provided, for each chemical. These chemical pumps shall be driven by individual motors, one for sulfuric acid transfer and the other for caustic solution transfer.

The unit shall be designed to minimize consumption, and its guaranteed values shall be satisfied [63–75].

### ***2.8.3 Demineralized Water Quality***

The following data on demineralized water quality shall be specified [5–8]:

- Electrical conductivity.
- Total hardness.
- Silica.
- pH.
- Other requirements.

### ***2.8.4 Type of Demineralizing Unit***

Type of demineralizing unit is to be decided, based on the raw water analysis. The use of a two-bed two-tower, two-bed three-tower unit or others suitable for the specified raw water quality and treated water quality shall be considered.

- The unit shall continuously produce a net flow to the service. However, where adequate demineralized water storage is available to meet standby and service requirements, a single unit may be permitted.
- Expected turndown ratio of a demineralized water flow rate to a designed value shall be suitable for boiler feed operation, as specified.

The demineralizing unit shall be installed in a non-hazardous area. Therefore, the unit shall be designed for suitable outdoor installation.

Cation/anion resin vessels shall be made of carbon steel with an inner rubber lining or equivalent to protect against corrosion.

Where diluted sulfuric acid and caustic soda are used, vessel internals shall be made of rubber-lined carbon steel, Type 316 stainless steel or equivalent [75–84].

### ***2.8.5 Performance Characteristics***

- The following performance characteristics shall be guaranteed:
- Treated water output capacity per hour and per cycle.
- Inlet water flow rate of both operation and regeneration.
- Treated water quality per items:
- Electrical conductivity.
- Silica.
- Total hardness.
- pH at 250 °C.
- Operating/regeneration cycle time.
- Chemicals both for regeneration and for neutralization per cycle (kg/cycle) and per each treated water (kg/m<sup>3</sup>).
- Waste water quantity per cycle (m<sup>3</sup>/cycle) and per each treated water (m<sup>3</sup>/m<sup>3</sup>) [68–73].

## 2.9 Miscellaneous Processes

Reverse osmosis (RO) is a membrane-technology filtration method that removes many types of large molecules and ions from solutions by applying pressure to the solution when it is on one side of a selective membrane. The result is that the solute is retained on the pressurized side of the membrane and the pure solvent is allowed to pass to the other side.

### 2.9.1 Reverse Osmosis

The applied pressure for brackish water purification is typically in the range of 2,760–4,140 kPa (ga) [27.6–41.4 bar (ga)] and for seawater purification, in the range of 5,520–6,900 kPa (ga) [55.2–69.0 bar (ga)].

Recovery of product (desalted) water with reverse osmosis units ranges from 50 to 90 % of the feedwater depending upon the feedwater composition, the product water quality requirement and the number of stages utilized.

For water containing from about 250–1,500 mg/kg dissolved solids, an economic comparison of ion exchange and reverse osmosis is recommended to select the more cost effective process.

Reverse osmosis may be considered for desalination of seawater.

In many cases, the reverse osmosis product water shall be treated by one of the ion exchanger processes, if high quality feedwater is required.

A pre-treatment system shall be provided to avoid fouling or excessive degradation of the membrane. Typically pre-treatment will include filtration to remove suspended particles and addition of chemicals to prevent scaling and biological growth.

Heating feedwater to provide optimum operating temperature of 25 °C for reverse osmosis system shall be considered.

Process design of reverse osmosis system shall be based on feedwater and product water qualities and rates. Different types of reverse osmosis modules layouts, for example, parallel, series including reject staging and product staging shall be proposed by Vendor(s) and the final configuration will be selected upon Company's approval [62–71].

### 2.9.2 Electrodialysis

Recovery of product (deionized) water with electrodialysis units ranges from 50 to 90 % of the feedwater depending upon the number of stages and degree of recirculation utilized.

Operating cost consists mainly of power costs (typically 1.6–2.7 kWh/m<sup>3</sup> of product water) and membrane cleaning and replacement costs.

Based upon combined capital and operating costs, the electrodialysis process is most economical when used to desalt brackish water (1,000–5,000 mg/kg dissolved solids) to a product water concentration of about 500 mg/kg dissolved solids. Process design of electrodialysis unit shall be based on feedwater and product water qualities and rates.

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